THROUGH SPACE AND TIME: AN EXAMINATION OF MOTION IN MULTIPLE OBJECT TRACKING

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To my parents and brother for their continual encouragement and support

and

to my husband, Eric, for his love and optimism

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CHAPTER 1

INTRODUCTION

We live and interact in a dynamic environment. People and things move around, often simultaneously. When we watch a basketball game, several players move on the court, the ball moves, and the referees also move. Our visual systems organize all of the visual information from the basketball scene into visual representations of people and things we are able to recognize. The visual information received from the objects may change during the game, but the visual system is able to create stable percepts of the objects. When Michael Jordan moves around the court, we see him from many different angles. Yet, we do not perceive a new person each time we see him from a new perspective. Instead, we perceive Michael Jordan running down the court. Not only do we perceive Michael Jordan running, we perceive the other players. Even though our visual information changes, the visual system is able to maintain the identities of several players moving on the court. The process by which we match the identities of the players to their positions on the court is object correspondence. Cognitive scientists study object correspondence to better understand how our visual systems create stable percepts of moving objects. As an object moves among other objects, how do we maintain the identity of the object over time? Said another way, how do we know that the object we see at one point in time corresponds to the same object in a new location later in time?

The purpose of this dissertation was to investigate whether the visual system uses the motion of objects to solve the object correspondence problem. When objects move, they leave their current locations and appear at new locations later in time. How does the visual system know which object moved to which new location? Returning to the basketball example, how do we know that Michael Jordan moved toward the basket and Dennis Rodman moved toward the half-court line? Parts of our brain are sensitive to motion and create representations of the speed and direction of objects that can be used by other areas of the brain. The object correspondence process may have access to these motion representations and use them to link the locations of objects to their identities. We know the player that moved closer to the basket is Michael Jordan because the percept of his motion was in the same direction as the basket. This dissertation will provide evidence that the visual system uses predictions from motion to keep track of moving objects.

Object correspondence without feature information

In a typical scene, our visual system has a wealth of information it can use to solve the object correspondence problem. When basketball players move on the court, we can use distinguishing information, such as their heights, the color of their jerseys, their jersey numbers, and their motion to help us determine who moved where. In order to determine whether motion is used to keep track of objects, other distinguishing information about the objects needs to be removed. When objects are identical, the only information the visual system can use to solve the correspondence problem is position and motion. Cognitive scientists use the multiple object tracking (MOT) paradigm to study how we maintain the identities of moving objects when distinguishing features are unavailable.

The MOT paradigm was first used to show that people can simultaneously maintain the identities of several moving objects without the use of distinguishing feature information

(Pylyshyn & Storm, 1988). In MOT experiments (Figure 1.1), the observer sits in front of a computer screen displaying several identical objects. At the beginning of the trial a subset of the objects are cued as targets by changing color or flashing for a brief period. The cues are removed and all the objects begin moving independently around the display. At the end of the trial, the observer designates which objects were targets by either clicking on the targets or responding to a probed object with a yes/no button press. Observers must keep track of the targets as they move throughout the trial using only position and motion information. The many variants of the MOT task have repeatedly shown that people can keep track of four or five targets (Intriligator & Cavanagh, 2001; Pylyshyn, 2006; Pylyshyn & Storm, 1988; Scholl & Pylyshyn, 1999; Scholl, Pylyshyn, & Feldman, 2001; Sears & Pylyshyn, 2000; Yantis, 1992), even when they move behind an occluder or disappear for a brief period of time (Fencsik, Klieger, & Horowitz, 2007; Horowitz, Birnkrant, Fencsik, Tran, & Wolfe, 2006; Keane & Pylyshyn, 2006; Scholl & Pylyshyn, 1999), clearly demonstrating the object correspondence problem can be solved using only position and motion information. In addition, tracking becomes more difficult as we try to keep track of more objects (Alvarez & Franconeri, 2007; Oksama & Hyönä, 2004), as the spacing between objects decreases (Alvarez & Franconeri, 2007; Intriligator & Cavanagh, 2001; Pylyshyn, 2004; Shim, Alvarez, & Jiang, 2008), or as the objects move faster (Alvarez & Franconeri, 2007; Liu et al., 2005), suggesting that object correspondence relies on a limited cognitive resource.

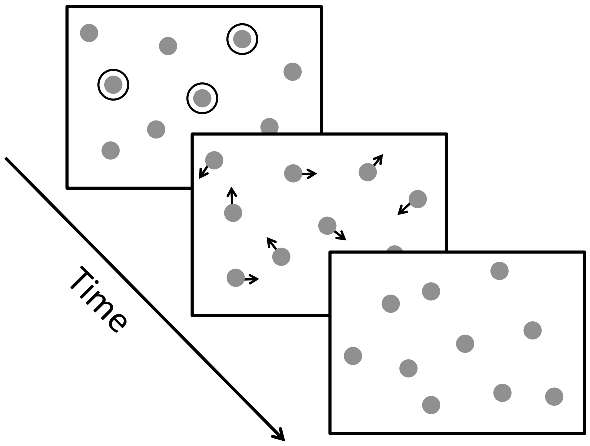


Figure 1.1. Illustration of the multiple object tracking task. Participants are presented with a set of objects and a subset are cued as targets (black rings). The cues are removed and all objects move independently around the display. Arrows are for illustrative purposes; they do not appear on the display. Participants track the targets while they move. At the end of the tracking period, the objects stop moving and the participants identify the targets.

Theories of tracking in relation to object correspondence

Current theories of MOT raise many interesting questions about how the visual system solves the object correspondence problem during tracking. Is object correspondence a serial or sequential process? Is attention necessary for object correspondence? Do we use predictions from motion to solve the object correspondence problem? In this section I will describe how the visual index theory, the multifocal theory of attention, the model of multiple identity tracking, and the probabilistic assignment model answer these questions about object correspondence.

The MOT paradigm was developed from predictions made by the visual index theory (or FINST theory) about how we maintain representations of objects that are not focally attended (Pylyshyn & Storm, 1988). At the time this theory was developed, researchers believed that people selectively attend to one location at a time. Attention was believed to move quickly from one region of the visual field to another to perform a variety of tasks. This view of attention seemed to imply that objects outside the region of attention were not processed. Pylyshyn suggested that a limited number of pre-attentive indexes bind to features in the brain's representation of a visual scene to provide access to unattended objects. The index "sticks" to the feature, moving as the retinal location of the feature changes (Pylyshyn, 1989; Pylyshyn, 2001, 2006; Pylyshyn & Storm, 1988). The indexes do not provide any feature information about objects; rather, they provide a reference to the locations of the objects. The indexes are like addresses to the locations of the targets. Attention can use these "addresses" to move to the location of an object in the display. After attention has moved to this location, it can process other information about the object, such as color or shape. The indexes stick to objects and update the locations of targets as they move, solving the object correspondence problem pre-attentively. The visual index theory predicted people would be able to simultaneously track multiple target objects moving among identical objects. Pylyshyn and Storm (1988) demonstrated that people are able to perform this task. Further, they showed human performace was better than a serial model of tracking. Consistent with the visual index theory, these results demonstrated that targets are tracked in parallel, not serially.

The visual index theory assumes there is a single focus of attention; however, the multifocal theory of attention says that we have multiple, independent foci of attention (Cavanagh & Alvarez, 2005). The foci of attention allow us to attend to multiple locations simultaneously. Objects attract foci of attention, and a control process keeps the foci of attention centered on the objects when they move. According to this theory, object correspondence requires attention. We maintain the identities of moving objects because attention moves with the object. In the tracking task, we know which objects are targets because we attend to the targets as they move. Attention selects objects in the display for processing, and an encoding stream sends information about these objects to other cognitive processes. The foci of attention draw from a common resource. As the number of foci increases, the amount of information processed by each of the foci decreases. When the number of foci reaches the limit of the capacity of attention, the foci of attention are only able to process the locations of objects.

The theories discussed so far propose ways the visual system may solve the object correspondence problem without knowing anything about the identities of objects; however, we are often able to use information about the identities of objects to help us keep track of them as they move. In the basketball example discussed previously, we know the name of the basketball player and may use that information to help us keep track of him on the court. The model of multiple identity tracking (MOMIT) describes a serial mechanism that allows identifying information to aid in solving the object correspondence problem (Oksama & Hyönä, 2008). This model describes how what we know about an object is bound to the object's location over time. Similar to the previously discussed models, the locations of objects are processed simultaneously. A separate process accesses the identities of objects, and this information is sent to a storage area where attention binds the identity to the location of the object. Only one object is focally attended at any given time, resulting in a serial process that binds the identity of the object to the location of the object. The strength of location-identity bindings weakens over time. When attention moves, it moves to the location of the weakest location-identity binding. If the object is no longer at this location, attention moves to the nearest object. Identity information can then be used to determine if this object is a target. For example, when we track Michael Jordan, we can ask if the attended player looks like him to determine if we are tracking the correct player. If it is the target, the location-identity binding is updated. If it is not the target, attention again moves to the nearest object. The process repeats until the target is found. Our ability to keep track of targets in the MOT task depends on the speed of objects because the serial updating of location-identity bindings takes time (Oksama & Hyönä, 2004, 2008). As time passes, an object will move from the location stored in memory. High-speed objects will move farther from the stored location in a given period of time than low-speed objects. As the distance between the current location of a target and the remembered location of the target increases, the chance of committing a tracking error increases. When objects are identical, they may be tracked using only position information or by using the motion of the objects as a feature to distinguish a target from a distractor.

The probabilistic assignment model provides a Bayesian approach to tracking (Vul, Frank, Tenenbaum, & Alvarez, 2009). In this model, spatiotemporal information is used to predict where objects are going, but there is some uncertainty associated with these predictions. The probabilistic assignment model uses position and velocity information to predict which objects are targets and which are distractors at any given moment during tracking. The predicted locations of targets and distractors are compared to the locations of objects on the display. The combination of target-distractor identities that minimizes prediction error is assumed to be correct. The comparisons are performed serially, but identities are assigned to all objects simultaneously. The model assumes people know how predictably the objects will move and this knowledge determines the extent to which velocity information is used during tracking. When predictability is assumed to be high, velocity is used to perfectly predict the future locations of objects. However, when predictability is assumed to be low, velocity is not used during tracking. Using data from human participants, Vul and colleagues (2009) showed that people do not assume predictable motion, and suggested little motion information is used during tracking. However, they acknowledge that there are several features of the MOT display that may affect whether or not motion is used during tracking. Thus, the probabilistic assignment model solves the object correspondence problem by using position, and possibly motion, information to form predictions about the future locations of objects.

Thus far, I have discussed four theories of multiple object tracking: the visual index theory, the multifocal attention theory, the model of multiple identity tracking (MOMIT), and the probabilistic assignment model. Each theory provides unique insights into the object correspondence problem. The visual index theory raises the possibility that object correspondence uses pre-attentive indexes to simultaneously update the locations of objects (Pylyshyn & Storm, 1988). The multifocal theory of attention assumes attention solves the correspondence problem for all objects simultaneously (Cavanagh & Alvarez, 2005). MOMIT uses identity information to resolve the correspondence problem through a serial location-identity binding process (Oksama & Hyönä, 2008). Finally, the probabilistic assignment model raises the possibility that the visual system makes predictions about where things are going to solve the object correspondence problem (Vul et al., 2009). The question of whether the visual system uses motion information to make predictions during tracking is the focus of this dissertation. In the following section I will develop specific hypotheses about the use of motion during tracking and relate those hypotheses to the theories of tracking.

Position and motion hypotheses

A question raised by the discussion of current theories of tracking is whether or not the visual system uses predictions from motion to solve the object correspondence problem. To help examine this question, I have developed two hypotheses about how the locations of objects are updated. If the object correspondence process makes predictions about the future locations of objects, it would be useful to have representations of object motion that can be used to track moving objects. I will refer to the hypothesis that motion information is used during tracking as the motion hypothesis. If the object correspondence process does not use predictions, motion information may not be used to track objects. Instead, objects may be tracked by updating their locations after they move using a proximity rule. I will refer to the hypothesis that the locations of objects are updated as the position hypothesis. In this section, I will discuss the position and motion hypotheses and how they relate to current theories of tracking.

The position hypothesis is that we are able to keep track of moving objects by updating their locations when they move from one position to the next without using motion. During the cue period the spatial locations of targets are encoded. Following the cue period, all objects move. The new locations of the objects are compared to the last known target locations (Figure 1.2A). The object that is closest to the remembered location of the target is assumed to be the target and this location is encoded. This process is continued throughout the tracking period in order to keep track of targets. Tracking errors may occur if two objects are equidistant from the remembered location of the target (Figure 1.2B). It is impossible for the visual system to know which object is the target, because both objects are the same distance from the last known location of the target. Errors occur when position information in not sufficient to distinguish targets from distractors.

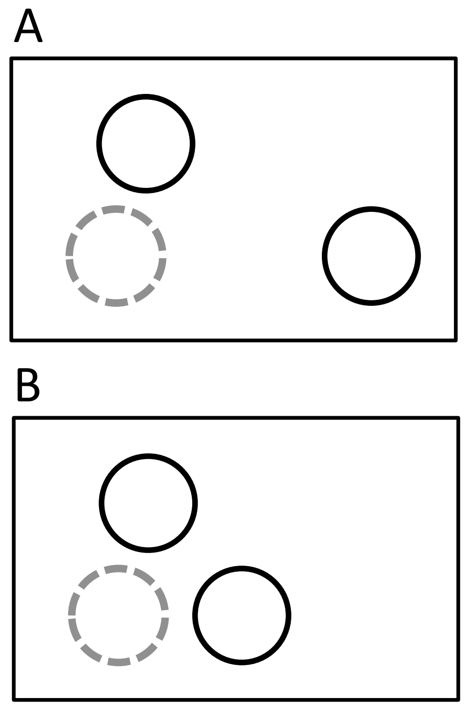
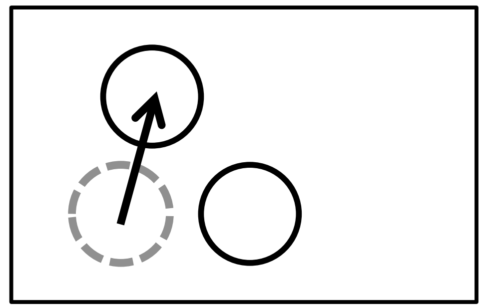


Figure 1.2. Illustration of the information used by the position hypothesis. According to the position hypothesis, the new target position is the one closest to the last-known location of the target (dotted circle). The solid circles show the locations of two objects currently visible during the tracking period. Only one of the solid circles is the target. On the top panel (A), the position hypothesis would select the top dot as the target. On the bottom panel (B), both objects are the same distance from the last known location of the target. The position hypothesis does not have a way to determine which object is the target.

The position hypothesis is consistent with all of the current theories of tracking. It could be derived from the indexes proposed by the visual index theory (Pylyshyn & Storm, 1988). The indexes serve as references to the locations of objects. The indexes stick to objects and move with them to update the representation of the object's location as it moves. In fact, the indexes only provide information about the locations of objects. The visual index theory would add to the position hypothesis that all locations are updated in parallel. The multifocal theory of attention would also add the prediction that locations are updated in parallel (Cavanagh & Alvarez, 2005). Unlike the visual index theory, it would predict that attention updates the locations of objects. The locations of objects are updated when the foci of attention move. MOMIT describes a serial component of tracking that is almost identical to the position hypothesis (Oksama & Hyönä, 2008). It predicts the last known locations of target objects are stored in memory. A single focus of attention moves to the object closest to the remembered location of a target. When attention is focused on a target, it updates the location of the target in memory. Thus, MOMIT would add the prediction that the locations of targets are updated serially. Finally, the position hypothesis is almost identical to the probabilistic assignment model when the predictability factor is zero (Vul et al., 2009). The predictability factor determines how much motion information is used during tracking. When this factor is zero, only location information is used to determine which objects are targets.

In contrast to the position hypothesis, the motion hypothesis is that motion is also used during tracking. The middle temporal (MT) visual area of the brain creates motion representations that give rise to our percepts of motion (Adelson & Movshon, 1982; Andersen, 1997; Born & Bradley, 2005). The motion representations may be used by the tracking mechanism in two different ways. First, motion representations may be used as feature information, such as color or shape. As a feature, motion information may be used to discriminate targets from distractors. This may be especially useful for determining which object is the target when two objects appear equidistant from the last known location of the target (Figure. 1.3). If these objects are moving in different directions and the direction of the target is known, the object moving in the same direction as the target will be selected as the target. Second, motion information may be used to predict where the target is going (Hogendoorn, Carlson, & Verstraten, 2008; Ramachandran & Anstis, 1983; Schwiedrzik, Alink, Kohler, Singer, & Muckli, 2007). If the speed and direction of the target are known, the exact location of the target at a given time in the future can be predicted. These predictions may also be used to determine which object is the target when two objects appear equidistant from the last known location of the target. The object at the predicted location will be selected as the target. Thus, motion information can be used to distinguish targets from distractors, preventing tracking errors.

Figure 1.3. Illustration of the information used by the motion hypothesis. The dotted circle shows the last-known location of the target. The solid circles show the locations of two objects currently visible during the tracking period. Only one of the solid circles is the target. The arrow represents the velocity of the target. Both objects are the same distance from the last known location of the target. Motion information can be used to determine which object is the target.



The motion hypothesis is not consistent with all theories of tracking. The indexes proposed by the visual index theory only provide information about the locations of objects (Pylyshyn & Storm, 1988). No feature information is associated with the indexes, so motion cannot be used to update the locations of the targets. Similarly, position information is used to update the locations of targets in MOMIT (Oksama & Hyönä, 2008). However, MOMIT uses knowledge about objects can be used to recover targets that move from their remembered location. If motion information is bound to the location of the target, motion could be used to determine which object is the target when two objects appear equidistant from the location of the target stored in memory. The multifocal theory of attention says information about objects is streamed from the foci of attention to be used by cognitive processes (Cavanagh & Alvarez, 2005). Motion information may be processed and used by the control process to move the foci of attention. The probabilistic assignment model predicts that motion is used during tracking when the predictability factor is greater than zero (Vul et al., 2009). The predictability factor determines how predictably objects are moving. When this factor is at its highest, objects move in perfectly predictable paths without any unexpected changes in motion. When the predictability factor is lower, object motion may change unexpectedly, so less motion information is used during the prediction stage of tracking. The probabilistic assignment model is the same as the motion hypothesis when objects move predictably.

I have discussed how the position and motion hypotheses are consistent or inconsistent with current theories of tracking. The position hypothesis is that only the locations of targets are used during tracking; motion information is not used during tracking. The motion hypothesis is that motion information is used during tracking. Most of the current theories of tracking are not explicit about whether motion is used during tracking. Thus, they may be consistent with both hypotheses. Investigations of whether motion information is used during tracking may shed some light on which hypothesis is correct. Next, I will discuss previous studies that have investigated whether or not motion information is used in tracking.

Support for the position hypothesis

The position hypothesis is that only the position of objects is used to track targets. Motion information is not used during tracking to predict the future locations of targets or to discriminate targets from distractors. Returning the basketball example, we may track Michael Jordan using only his location on the court. We know he is currently standing on the half-court line. When he moves, he is no longer at this location. In order to find his new location, we look for the player nearest the half-court line. In this example, we do not need to know which direction he is running or how fast he is moving. Instead, we compare the locations of players on the court to Michael Jordan's last known location. The benefit of the position hypothesis is that it provides a way to track objects that move in unexpected ways. Evidence for the position hypothesis comes from studies that show motion is not used predictively when objects disappear (Fencsik et al., 2007; Franconeri, Pylyshyn, & Scholl, 2012; Keane & Pylyshyn, 2006) and distance, not speed, limits tracking (Franconeri, Jonathan, & Scimeca, 2010; Franconeri, Lin, Enns, Pylyshyn, & Fisher, 2008). In this section I will examine the evidence for the position hypothesis.

One way to test whether motion is used during tracking is to examine how targets are recovered after they disappear for a brief time. When an object disappears, motion may be used to predict where it will reappear. However, this is not necessarily the case. The position hypothesis predicts that the object is recovered better when it appears closer to the location where it disappeared, regardless of whether that location matches predictions from motion. To test this, studies have used a variant of the MOT paradigm in which objects disappear for a brief period during tracking. While the objects are invisible, they either stay in their last visible location or continue moving. Consistent with the position hypothesis, people were better able to recover the targets when they reappeared in the same location where they had disappeared than if they reappeared as if they had continued moving during the blank period (Fencsik et al., 2007; Keane & Pylyshyn, 2006). Further, tracking accuracy declined when targets reappeared farther away from the location where they disappeared (Keane & Pylyshyn, 2006). However, a replication and extension of this study demonstrated a benefit of viewing motion before the blank period when people tracked two targets, but not when they tracked four (Fencsik et al., 2007). Targets were recovered better when objects moved before the blank period than when they remained stationary before the blank period when observers tracked two targets, suggesting that motion may be used to track a limited number of targets. A more recent study examined whether the sudden disappearance of the objects may have resulted in the finding that motion is not extrapolated during tracking (Franconeri et al., 2012). In this study, objects passed behind vertical bars instead of suddenly disappearing. In the first experiment, the objects were displaced vertically during occlusion by either two or four object diameters. Tracking accuracy was better when the vertical shift was smaller, i.e. when objects reappeared closer to the location where they disappeared. In another experiment, objects either kept the same trajectory while they were occluded or changed direction by 30° or 60° while they were occluded. Tracking accuracy was unaffected by the change in direction during occlusion, suggesting that motion information was not used to predict where the targets would reappear. These results suggest that motion information is not used to recover targets during tracking, consistent with the position hypothesis.

Another line of evidence favoring the position hypothesis comes from examinations of the effect of speed on tracking. Tracking difficulty increases as the speed of objects increases (Alvarez & Franconeri, 2007; Liu et al., 2005; Tombu & Seiffert, 2011). It has recently been suggested that the distance travelled by an object and crowding, not speed, limit tracking (Franconeri et al., 2010; Franconeri et al., 2008). Numerous studies have shown that tracking is more difficult when objects are closer to one another (Alvarez & Franconeri, 2007; Intriligator & Cavanagh, 2001; Pylyshyn, 2004; Shim et al., 2008; Tombu & Seiffert, 2011). In the typical MOT display, objects move within a framed region of space. In this display, objects get close to one another more often as their speed increases, increasing the likelihood that a target will be confused with a distractor. One study manipulated speed while controlling for crowding and distance travelled during tracking (Franconeri et al., 2010). In this study, each target was paired with a distractor and the pairs of dots rotated about their central point (Figure 1.4). Across blocks of trials the speed of rotation and tracking duration varied. Because the pairs of dots rotated about a central point, the amount of crowding did not change throughout the tracking period. The distance travelled during tracking limited performance, not the speed of the dots. That is to say, dots that moved farther at a slow speed were harder to track than dots that moved a shorter distance at a fast speed. There was no difference in tracking accuracy between dots that moved the same distance at different speeds. This result is consistent with the proposal that speed does not limit tracking. Instead, tracking is limited by how far targets travel during tracking. The position hypothesis is that motion, and thus speed, is not used during tracking. Thus, these results are consistent with the position hypothesis.

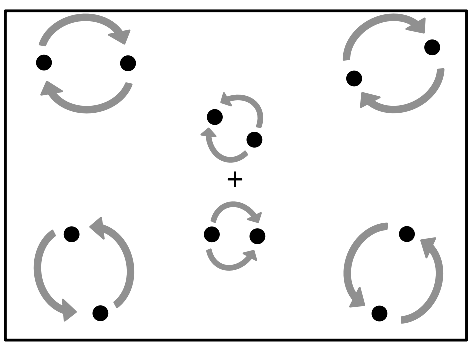


Figure 1.4. Illustration of the tracking task used by Franconeri, Jonathan, and Scimeca (2010) illustrating the multiple object tracking task. The arrows represent the rotation of the dots but were not present in the display.

Support for the motion hypothesis

The motion hypothesis is that motion information is used during tracking. Although studies that have used disappearing objects (Franconeri et al., 2012; Keane & Pylyshyn, 2006) and speed manipulations (Franconeri et al., 2010; Franconeri et al., 2008) have not found evidence for the use of motion information during tracking, other studies have found evidence consistent with the motion hypothesis (Horowitz & Cohen, 2010; Iordanescu, Grabowecky, &

Suzuki, 2009; Seiffert & St.Clair, 2010; St.Clair, Huff, & Seiffert, 2010). In this section, I will review findings that suggest motion information is used during tracking.

Previous work has shown that motion information is available to the tracking mechanism and may be used during tracking (Blake, Cepeda, & Hiris, 1997; Horowitz & Cohen, 2010; Shooner, Tripathy, Bedell, & Ogmen, 2010). Horowitz and Cohen (2010) showed that people could report the direction of targets in an MOT task. Participants tracked a variable number of targets and at the end of the tracking period a random object was probed. Participants reported whether the object was a target or a distractor and adjusted an arrow to extending from the object to point in the same direction the object was moving. People were able to report the direction of targets and the direction of distractors. The precision of direction reports was higher for targets than for distractors. Further, precision decreased when people tracked more targets, suggesting that the use of motion information draws on a limited resource during tracking. Motion information may have been remembered in this task because participants knew they would need to report the direction of motion of one of the objects. Without this task demand, motion information may not be used during tracking. Iordanescu and colleagues (2009) found evidence for the use of motion during tracking using a localization task. The task used the MOT paradigm but the objects disappeared at the end of the trial. Participants used the mouse to click on the disappearance location of one randomly selected target. They found that the response location was related to the target's velocity. People tended to select locations that were in the same direction as the target's trajectory. Further, the distance between the disappearance location and the selected location was larger for fast moving objects than for slow moving objects. Taken together, these findings suggest that motion information may be used to extrapolate the future locations of targets.

The studies discussed thus far have not examined whether motion is used *during* tracking. These studies demonstrate that motion is remembered after tracking has stopped, but do not show that motion is used while the objects are moving. We recently found evidence that motion is used during the moment-to-to moment tracking of objects that remain visible (St.Clair et al., 2010). We assumed the motion inside objects is integrated with the motion of the object's borders (Lorenceau, 1996; Qian, Andersen, & Adelson, 1994; Weiss, Simoncelli, & Adelson, 2002). Thus, manipulating the direction of motion inside the object would change the motion representation used during tracking without changing other features of the tracking display, such as crowding. In this study, objects were filled with a random-dot texture and presented on a background with the same random-dot texture. The texture inside the objects either remained stationary or moved relative to the motion of the objects (Figure 1.5). Moving texture within the objects moved in the same direction as the object, in the opposite direction of the object, or orthogonal to the object's trajectory. The speed of the texture motion was adjusted across conditions so that the speed of the texture was always 2.2°/s relative to the background. No difference in tracking accuracy between texture conditions would be evidence that the tracking mechanism does not use motion information. However, a difference in tracking accuracy between texture conditions would be evidence that the tracking mechanism uses motion information. Consistent with the motion hypothesis, we found that the direction of the texture motion influenced tracking accuracy. Tracking accuracy was lower when texture moved in the opposite direction of the object compared to when it moved in the same direction as the object. I will refer to this finding as the texture effect. A second experiment demonstrated that tracking accuracy declined as the direction of the texture motion deviated farther from the object's direction of motion. The final experiment found a texture effect for luminance-defined balls moving on a 3-D rendered plane, demonstrating that the texture effect is not unique to second-order stimuli moving in 2-D space. Our results show that motion is used in the moment-to-moment tracking of visible objects.

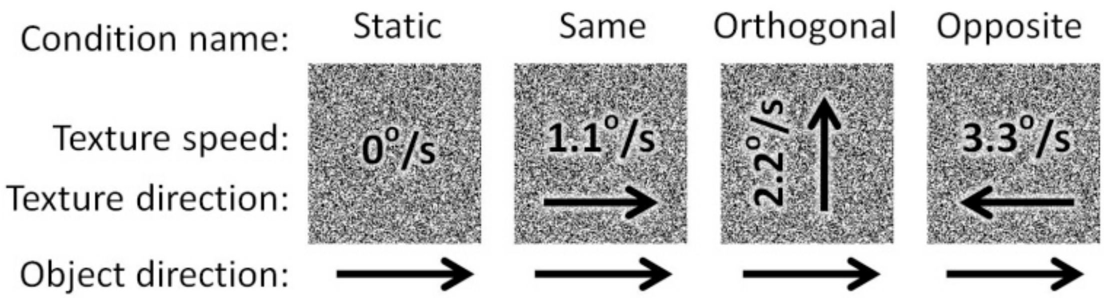


Figure 1.5. Figure 1 from St.Clair, Huff, and Seiffert (2010) illustrating the texture conditions. Arrows under the square indicate the direction of the object moving at 1.1°. Arrows inside the square indicate the direction of the texture motion. The value inside the square is the speed of the texture relative to the object.

In follow-up experiments, we whether or not motion information is used to predict the future location of targets (Seiffert & St.Clair, 2010). Similar to the probabilistic assignment model (Vul et al., 2009), we reasoned that more motion information is used when objects follow predictable paths than when objects move randomly. When objects move predictably, we can accurately predict where they will be in the future. However, when objects change direction unexpectedly, our predictions will be wrong. If motion is used for prediction during tracking, conflicting textures should only influence tracking when objects move predictably. Observers tracked either grey objects or objects filled with random-dot texture. The texture remained static, moved in the same direction as the object, or moved in the opposite direction of the object. The objects either followed linear paths or random paths. When the objects followed random paths, they changed direction on every frame with the restriction that the direction change was not more than 20° from the current direction of motion. The results were consistent with the prediction that less motion information is used when the objects move unpredictably. Grey objects were harder to track when they followed random paths than when they followed linear paths. Further, objects with opposite moving textures were tracked worse when moving in linear paths than when moving in random paths, resulting in a smaller texture effect for objects following random paths than for objects following linear paths. The finding that motion information is used less when objects in the display changed direction unexpectedly, suggests motion information is used to predict the future locations of targets.

How does the visual system know when to limit the use of motion information? One possibility is that the visual system uses prediction errors to determine when motion cannot be used to predict future target locations. At the beginning of the tracking period the visual system makes a prediction about where the targets will be in the future and then verifies that the targets appeared in the predicted locations. If the prediction is correct, the visual system continues to make predictions about the future location of targets. If the prediction is incorrect, the visual system limits the use of predictions to track the targets. Based on this logic, we assumed that motion information is less likely to be used during tracking when prediction errors increase. In a second experiment, we manipulated the degree of direction change, or turn angle, during the tracking period. Larger turn angles result in larger prediction errors, so it was expected that tracking accuracy would decline as turn angle increased. Consistent with Horowitz and Kuzmova (2010), we found that tracking accuracy declined as turn angle increased for grey objects. As with our first experiment, tracking accuracy improved as turn angle increased for objects with opposite moving textures, resulting in a smaller texture effect for larger turn angles. These results are consistent with the prediction that the size of prediction errors is used to determine when motion information is used to predict the future locations of targets. When prediction errors are large, as when targets make a large change in direction, less motion information is used during tracking. Taken together, our previous work suggests that motion information may be used to predict the future locations of targets during tracking (Seiffert & St.Clair, 2010; St.Clair et al., 2010) and thus, lend support to the motion hypothesis.

Brief overview

Our previous research showed motion information is used during the moment-to-moment tracking of objects that remain visible (St.Clair et al., 2010) to predict the future locations of targets (Seiffert & St.Clair, 2010). The goal of this dissertation is to better understand how motion is used during tracking. Chapter 2 investigated whether the position hypothesis can account for the texture effect found in our previous work by examining the effects of moving textures on direction reports. It concludes that moving textures affect the representation of direction used by the tracking mechanism, and does not support the position hypothesis. Chapter 3 investigated whether moving textures affect the representation of speed used during tracking by examining how moving textures affect localization errors. It concludes that moving textures do not affect the speed representations used during tracking. Finally, Chapter 4 investigated whether distractor motion is used during tracking by manipulating the texture motion of distractors independently of the texture motion of targets. It concludes that distractor motion is processed during tracking. From these results, I reject the position hypothesis and conclude that target motion and distractor motion are used in the moment-to-moment tracking of targets.

CHAPTER II

THE EFFECT OF TEXTURE MOTION ON DIRECTION REPORTS

Introduction

Our previous research showed that conflicting motion impairs tracking, but it did not show how moving textures impaired tracking (St.Clair et al., 2010). Objects filled with texture moving in a different direction than the object's trajectory were more difficult to track than objects filled with texture moving in the same direction as the object's trajectory. We claimed our results are evidence that motion is used during tracking. However, it is possible that the position hypothesis could account for our results. In this chapter, I examine errors in direction reports to determine whether moving textures alter the motion information used in tracking or whether they alter the perceived position of targets.

The position hypothesis can account for our previous findings if the moving textures altered the representation of the last known target location. Several studies have shown that objects are mislocalized in the direction of texture motion (Burr & Thompson, 2011; De Valois & De Valois, 1991; Matin, Boff, & Pola, 1976; Ramachandran & Anstis, 1990). Texture moving in the same direction as the target would shift the perceived target location ahead in the target's trajectory. This shift would decrease the distance between the remembered target location and the current target location. Conflicting textures would shift the remembered location of the target in the direction of the texture motion, which may be different from the target direction. As a result, the distance between the target and its last perceived location increases. This would have increased the likelihood that a distractor was closest to the last perceived position of the target, resulting in more tracking errors.

The motion hypothesis can account for our previous findings if moving textures alter the motion representations of objects. In our previous work, we assumed that the motion of the textures is integrated with the motion of the object (Lorenceau, 1996; Qian et al., 1994; Weiss et al., 2002). If this is the case, the texture motion will bias the motion representation of the object. For example, textures that move orthogonal to the object's direction of motion will be integrated with the object motion to form a motion representation that is biased toward the direction of the texture motion. Previous work has shown that motion information is remembered for multiple moving objects (Blake et al., 1997; Horowitz & Cohen, 2010; Shooner et al., 2010). We can use reports of an object's direction of motion to examine how moving textures influence the motion representations used during tracking.

Using the MOT paradigm, Horowitz and Cohen (2010) showed that people could report the direction of targets in a MOT task. During the cue period a number of objects flashed as targets. The number of targets varied between trials. Following the cue period, all of the objects began moving. Objects moved linearly, only bouncing when they reached the edge of the tracking area. At the end of the tracking period, all dots remained stationary and two classification tasks were performed. In one task, a probed dot turned blue and participants used a button press to identify it as a target or distractor. In the other task, a blue arrow protruding from the object's edge was presented. Participants used the mouse to rotate the arrow so that it pointed in the direction of the object's trajectory. People were able to report the direction of objects, but precision decreased as tracking load increased. Consistent with the motion hypothesis, this finding suggests motion information is used during tracking. Further, it suggests the use of motion information during tracking draws on a limited resource.

I used the methods of Horowitz and Cohen (2010) to test predictions about how moving textures influence direction reports. Similar to our previous work, I used textured objects moving on a textured background (St.Clair et al., 2010). The texture in the objects either remained stationary or moved relative to the direction of the object. At the end of the tracking period, an object was probed and participants reported the object's direction of motion. If objects with moving textures are more difficult to track because they are less visible, we will find no bias in direction reports for objects with moving textures. The position and motion hypotheses predict a bias in direction reports. I will examine these predictions, starting with the position hypothesis.

The position hypothesis makes specific predictions about how each texture condition will influence the reports of the object's direction of motion. As in the task used by Horowitz and Cohen (2010), direction reports will be given for stationary objects (time *t*) in this study. If participants compare the location of the target at time *t* to the last known location of the target during the tracking period (time *t-1*) they can use this information to report the direction of the target. Errors in direction reports may arise from an error in the memory of the target location at time *t-1* or from an error in deriving the direction of motion from the position information. If moving textures bias perception of the target location at time *t-1* in the direction of the texture motion, then opposite moving textures will cause the prior target location to be displaced backwards in the target's trajectory (see Figure 2.1). Derivation of direction from this location to the current location of the target will result in an accurate report. Similarly, same moving textures will displace perception of the target location at time *t-1* further ahead in the target's trajectory (see Figure 2.1). Again, direction reports will be accurate. However, direction reports for orthogonal textures will not be accurate; they will be biased in the direction opposite the texture motion. For example, if the target moves rightward and the texture moves upward, the perceived target location at time *t-1* will be above the actual location of the target. When this location is compared to the location of the target at time *t*, the direction report will be down and to the right (see Figure 2.1). To summarize, the position hypothesis predicts that direction reports will be accurate for objects with same or opposite moving textures, but will be biased in the direction *opposite* the texture motion for objects with orthogonal textures.

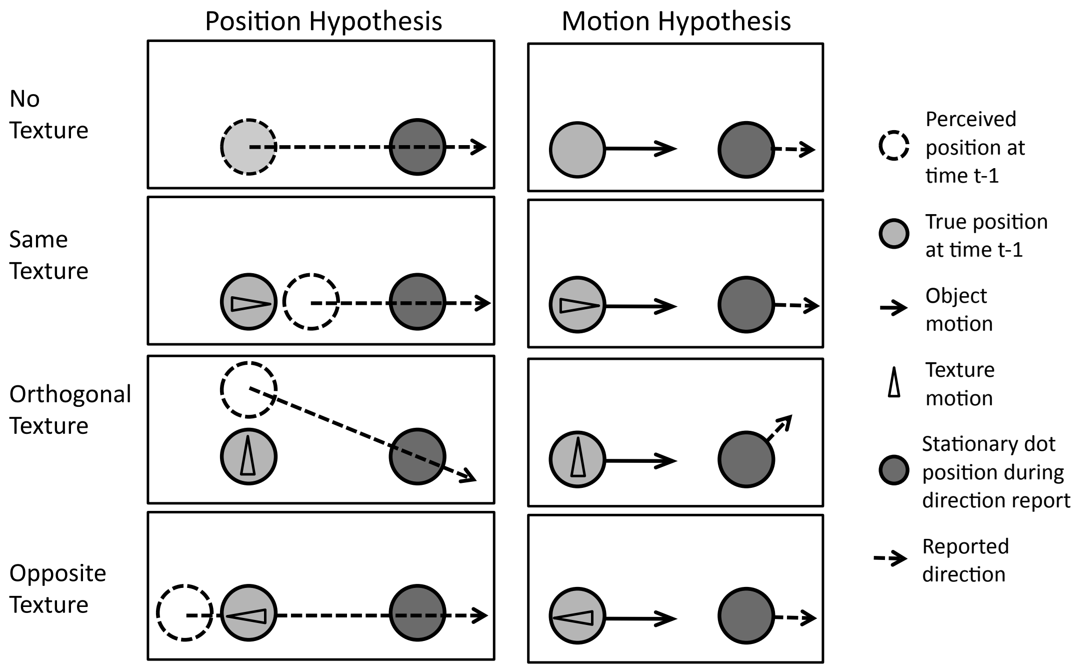


Figure 2.1. Predicted direction reports for the position hypothesis (left column) and motion hypothesis (right column) for each texture condition. The dark grey dot shows the location of the target when it is stationary at the time of the direction report (t). The light grey dot shows the location of the target at time *t-1*. The dotted circle shows the perceived location of the target at time *t-1*. The black triangle inside the light grey dot indicates the direction of the texture motion. The black arrow extending from the light grey dot indicates the direction of the target. The left column shows the position hypothesis's predictions of direction reports for each texture condition with dotted arrows. Direction is derived from the last known location of the target (dotted circle) and the location of the target at the time of response (dark grey dot). The right column shows the motion hypothesis's predictions of direction reports for each texture condition with dotted arrows. Direction information is represented as the vector average of target motion and texture motion throughout the tracking period.

The motion hypothesis makes different predictions about how moving textures will influence direction reports. Moving textures influence direction reports because the motion of the texture is combined with the motion of the object, possibly through vector averaging. This means the motion of the texture and the motion of the object are averaged with respect to their vectors. Because the task is to report the direction of the object motion, I will assume object motion is weighted more heavily than texture motion (Tse & Hsieh, 2006). For texture moving in the same direction as the target, there is no conflict of direction, so direction reports should be accurate (see Figure 2.1). For textures moving orthogonal to the target's direction, the vector average would be a combination of the target's motion and the texture motion (see Figure 2.1). This means that direction reports for targets with orthogonal moving texture should be biased in the direction of the texture motion. For example, if the object was moving to the right and the texture was moving upward, the reported direction should be up and to the right. For texture moving in the opposite direction of the target, this means motion in one direction will be combined with motion in the opposite direction (see Figure 2.1). This may affect the representation of speed, but direction reports should be accurate. Thus, the motion hypothesis predicts that direction reports will be accurate for same and opposite moving textures, but will be biased in the *same* direction as the texture for objects with orthogonal textures.

An alternative to the predictions of the motion and position hypotheses is that moving textures do not bias direction reports. One explanation for this prediction is that the texture motion and object motion are not combined. Rather, they are maintained as two separate motion representations that compete during tracking. This explanation predicts no bias in direction reports for all texture conditions, because the object motion is maintained independent of the texture motion. The other explanation is that moving textures alter the visibility of objects by degrading their borders. Objects with opposite moving texture are more difficult to see than objects with same moving texture, so objects with opposite moving texture are not tracked as accurately. This explanation predicts large errors in direction reports when people have difficulty seeing the objects. However, the errors of the direction reports should not be biased in any particular direction. Thus, direction reports for objects with opposite moving texture would have a higher error rate than direction reports for objects with same moving texture.

In summary, the position hypothesis predicts that errors in direction reports will be biased in the direction opposite the texture motion. The motion hypothesis predicts that errors in direction reports will be biased in the same direction as the texture motion. I expect to see the differences in these predictions with the orthogonal textures. Direction reports with no bias in the errors would indicate that the texture motion and object motion are maintained as separate motion representations. Finally, larger errors in direction reports for objects with conflicting texture motion would indicate that these objects are less visible if the errors are not biased in any direction.

Experiment 2.1: Direction reports with moving textures

I used methods similar to those of Horowitz and Cohen (2010) to determine whether moving textures influence direction reports through a position mechanism or a motion mechanism. Participants tracked dots filled with solid color or texture. The texture remained static, moved in the same direction as the object, moved orthogonal to the direction of the object or moved in the opposite direction of the target. At the end of the tracking period participants reported the direction of motion of one randomly chosen target. I compared direction reports to the direction of the target to determine whether moving textures altered the representations of direction used during tracking.

Participants

Thirteen undergraduates from Vanderbilt University participated in this experiment, following the procedures defined for the protection of human participants by Vanderbilt University and the APA Code (2002).

Apparatus

The stimuli were generated with a Mac Mini and presented on a 17-in, LCD monitor with a refresh rate of 75 Hz. Observers sat approximately 60cm from the display. Stimuli were produced by Matlab 7.5.0 (R2007b) for OS X version 10.5.5 and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) version 3.0.8.

Stimuli

Stimuli were 10 dots filled with random dot texture or solid grey color presented in a white frame filled with random-dot texture. The random-dot texture of the background was regenerated at the beginning of each trial and remained stationary throughout the trial. The frame was approximately 16° X 17°. The diameter of each dot was 1.0°. The initial positions of the dots were randomized with the constraint that dots did not overlap with each other or the frame's border. Green rings 1.2° in diameter outlined the borders of the dots to designate targets. Dots travelled at approximately 2.5°/sec and were permitted to overlap during the tracking period. Dots travelled in linear paths and bounced off the frame's borders by reflecting with an added amount of random jitter, between 6 and 11 angular degrees. On trials in which the dots were filled with texture, the texture moved relative to the dot's direction of motion at twice the object speed, approximately 5°/sec. The texture of each dot moved in the same, orthogonal, or the opposite direction relative to the dot's trajectory. Orthogonal textures always moved in the direction 90° counterclockwise from the dot's trajectory.

Procedure

Each participant completed one 60-minute session containing experimental trials and practice trials. Each trial began with the presentation of 10 dots, each with a black border. The cues, green rings, were presented for 2 sec to designate 3 dots as targets. The cues and black borders were removed and a tone was presented to designate the beginning of the tracking interval. The dots moved for 4 seconds. At the end of the trial, the black borders reappeared and the dots remained stationary. A blue pointer appeared and extended 2.5° from the edge of one randomly selected target. Participants were told to adjust the pointer to match the direction that the object was moving just before the end of the trial. They did this by using the mouse to rotate the angle of the pointer. When they were satisfied with the position of the pointer, participants pressed the spacebar and the next trial started after 2 sec. At the end of each block participants were encouraged to take a break. During practice, each condition was presented once for a total of 4 trials. During the experimental session, each condition was presented 7 times in each block. Five blocks were completed for a total of 35 repetitions per condition for each participant.

Data Analysis

Response errors were measured as the acute angle between the response direction and the direction of the target. Participants were instructed to report the direction immediately prior to the end of the tracking period. If the object bounced off a wall at the end of the trial, the reported direction was compared to the direction of the object after the bounce. Responses counterclockwise from the object direction were positive and responses clockwise from the object direction were negative. The orthogonal texture motion was always in the counterclockwise direction. Errors biased toward the direction of the orthogonal texture were positive and errors biased in the opposite direction of the orthogonal texture were negative. The error magnitude was computed as the absolute value of the response error.

Results and Discussion

Figure 2.2 shows the error magnitude for trials with solid grey dots, same moving texture, orthogonal texture, and opposite moving texture. A repeated measures ANOVA revealed that moving textures affected the accuracy of direction reports, $F(3, 36) = 22.78$, $p < .05$. Direction reports for targets with orthogonal textures were less accurate than direction reports for grey dots ($t(12) = -5.62$, $p < .05$) or same moving textures ($t(12) = 5.79$, $p < .05$). Similarly, direction reports for targets with opposite moving textures were less accurate than direction reports for grey dots ($t(12) = 4.88$, $p < .05$) or same moving textures ($t(12) = 4.42$, $p < .05$). Neither the motion hypothesis nor the position hypothesis predicted a decrease in accuracy for targets with objects with opposite moving texture. This finding will be examined further in Experiment 2.3.

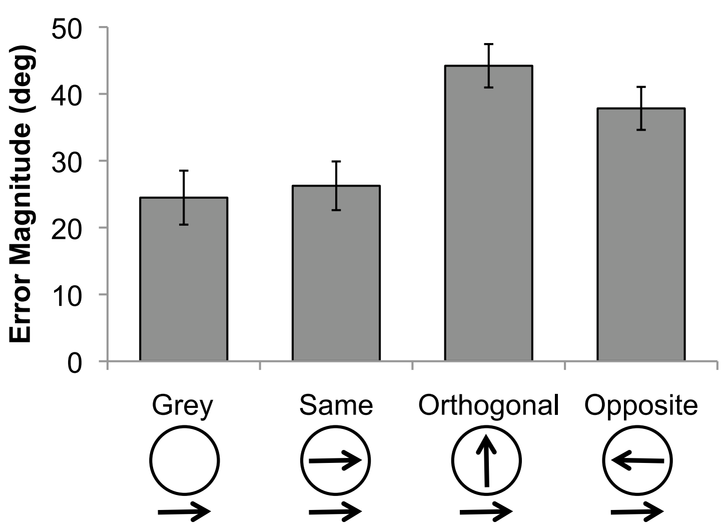


Figure 2.2. Error magnitude in direction reports for grey dots, same moving textures, orthogonal textures, and opposite moving textures in Experiment 2.1. Error bars represent the standard error. Arrows below the circles indicate the object direction and arrows inside the circles indicate texture direction.

The directions of response errors were examined to determine if there was any systematic bias in errors. Orthogonal textures always moved counterclockwise to the object's direction, so a positive response error would indicate a bias in the direction of the texture motion. Only orthogonal response errors were significantly different from zero ($M = 10.05$, $SD = 11.81$; $t(12) = 3.07$, $p < .05$) and were biased in the direction of the texture motion. Grey responses ($M = 0.76$, $SD = 9.98$; $t(12) = 0.27$, $p = .79$), same responses ($M = 3.58$, $SD = 8.27$; $t(12) = 1.6$, $p = .15$), and opposite responses ($M = 4.32$, $SD = 13.41$; $t(12) = 1.16$, $p = .27$) did not differ significantly from zero. These results match the predictions of the motion hypothesis.

Experiment 2.2: Direction reports with feedback

The results of Experiment 2.1 are consistent with the motion hypothesis, but it is possible that participants misunderstood the task. Participants were told to adjust the pointer so that it matched the probed target's direction of motion immediately before it stopped moving. It is possible, however, that participants adjusted the pointer to match the target's texture motion or that they adjusted the pointer to match a combination of the texture motion and the target motion. Experiment 2.2 was identical to the previous experiment, except I changed the response to make the task more clear and provided feedback about the accuracy of the direction reports to ensure that participants were performing the correct task.

Methods

The apparatus and stimuli were the same as that in the previous experiment. The procedure was the same as that used in Experiment 2.1 except the response differed. Instead of probing targets with a blue line, a red ring appeared around a randomly chosen target and a red dot 1.0° in diameter appeared at a random location 2.5° away from the target. Participants were told to adjust the red dot so that the target would hit it when the target resumed its movement (Figure 2.3). They did this by using the mouse to rotate the red dot around the target and pressing spacebar when they were satisfied with its position. After placing the dot, participants were shown a movie of the target continuing along its path while the red dot remained in the selected location. In addition to the visual feedback, auditory feedback was provided. A dinging sound was presented if the target hit the red dot to indicate a correct response. A buzzer sound was presented if the target did not hit the red dot to indicate an incorrect response. Eleven undergraduates from Vanderbilt University participated and were recruited as in Experiment 2.1.

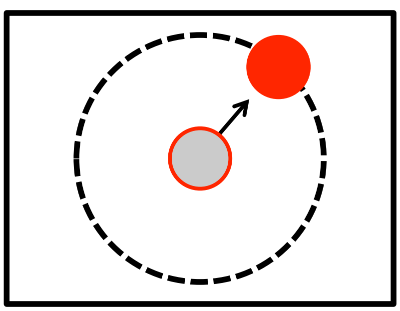


Figure 2.3. Illustration of the response task in Experiment 2.2. The grey dot is the target and the red dot is the probe. Participants rotated the red dot so that the target would hit the red when it resumed its motion. The arrow indicates the target's trajectory and the dotted circle is the path the red dot followed when rotated. The arrow and dotted line are for illustrative purposes only and were not presented in the experiment.

Results and Discussion

Figure 2.4 shows the error magnitude for trials with solid grey dots, same moving texture, orthogonal texture, and opposite moving texture. As with Experiment 2.1, conflicting texture reduced the accuracy of direction reports. Direction reports for targets with opposite moving texture were less accurate than those for grey dots ($t(10) = -4.12$, $p < .05$) or same moving texture ($t(10) = -3.42$, $p < .05$). Direction reports for targets with orthogonal texture were less accurate than those for grey dots ($t(10) = -5.65$, $p < .05$) or same moving textures ($t(10) = -4.0$, $p < .05$). Again, the response errors for targets with orthogonal textures were biased in the direction of the texture motion ($M = 6.61$, $SD = 5.68$; $t(10) = 3.86$, $p < .05$). These results match those of Experiment 2.1, indicating that my results are not the result of participants misunderstanding the task.

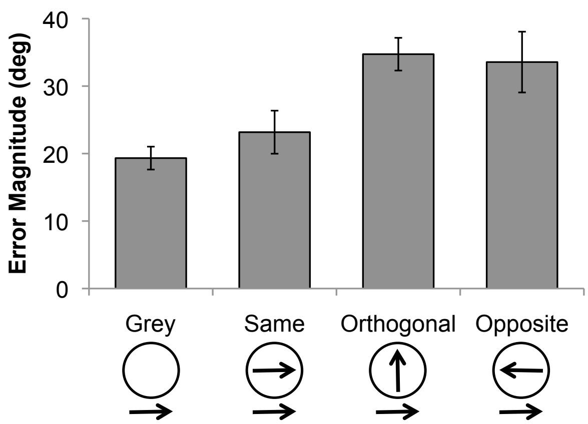


Figure 2.4. Error magnitude in direction reports for grey dots, same moving textures, orthogonal textures, and opposite moving textures in Experiment 2.2. Error bars represent the standard error. Arrows below the circles indicate the object direction and arrows inside the circles indicate texture direction.

Experiment 2.3: Direction reports for correctly tracked targets

Errors in direction reports are larger when texture motion conflicts with the object motion than when there is no conflict; however, it is also more difficult to track objects with conflicting texture motion (St.Clair, Huff, & Seiffert, 2010). Horowitz and Cohen (2010) showed that direction reports for distractors are less precise than direction reports for targets. Lost targets may be treated like distractors. It is, therefore, possible that direction reports for objects with conflicting texture motion had larger errors because the probed target was not tracked at the end of the trial. However, it is also possible that objects with conflicting texture motion were less visible. Because the objects were difficult to see, it was difficult to determine their direction of motion. Experiment 2.3 examined whether conflicting textures influence direction reports of correctly tracked targets.

Methods

The apparatus and stimuli were the same as that in Experiment 2.1. The procedure was also the same, except a probe task was added to measure tracking accuracy. In the probe task, a blue ring appeared around one dot at the end of the trial. Participants used button presses to indicate whether the probed dot was a target or a distractor. In half the trials the probed dot was a target. In the other half of the trials the probed dot was a distractor. The same dot was probed in the direction response task. The order of tasks was randomized between participants so that half the participants performed the probe task before the direction response task and half performed the probe task after the direction response task. Sixteen undergraduates from Vanderbilt University participated and were recruited as in Experiment 2.1.

Results and Discussion

Figure 2.5 shows tracking accuracy for trials with solid grey dots, same moving texture, orthogonal texture, and opposite moving texture. A repeated measures ANOVA for texture conditions revealed a main effect of texture $F(3, 45) = 11.75$, $p < .05$. Tracking accuracy declined as the texture motion deviated further from the object motion, replicating the findings of St.Clair and colleagues (2010).

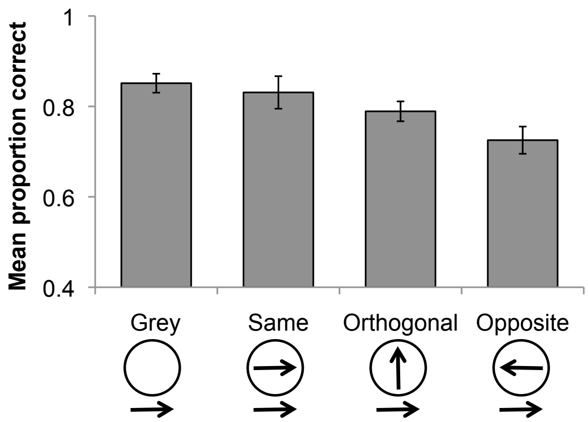


Figure 2.5. The mean proportion of correctly identified targets and distractors for grey dots, same moving textures, orthogonal textures, and opposite moving textures in Experiment 2.3. Error bars represent the standard error. Arrows below the circles indicate the object direction and arrows inside the circles indicate texture direction.

Figure 2.6 shows the error magnitude for correctly identified targets. Distractors and targets misidentified as distractors were not included in the analysis. A repeated measures ANOVA for texture conditions revealed a main effect of texture $F(3, 45) = 3.63$, $p < .05$. Direction reports for correctly tracked targets with orthogonal textures were less accurate than direction reports for grey targets ($t(15) = 3.25$, $p < .05$) or for targets with opposite textures ($t(15) = 3.03$, $p < .05$). No other comparisons were significant. Thus, the increased error in direction reports for opposite textures found in Experiments 2.1 and 2.2 are likely due to participants losing the probed target. However, the increased errors in direction reports for orthogonal textures persist for correctly tracked targets. The directions of response errors for correctly tracked targets were examined to determine if there was any systematic bias in errors. Only orthogonal response errors were significantly different from zero ($M = 9.90$, $SD = 12.28$; $t(15) = 3.23$, $p < .05$) and were biased in the direction of the texture motion. Again, these results match the motion hypothesis.

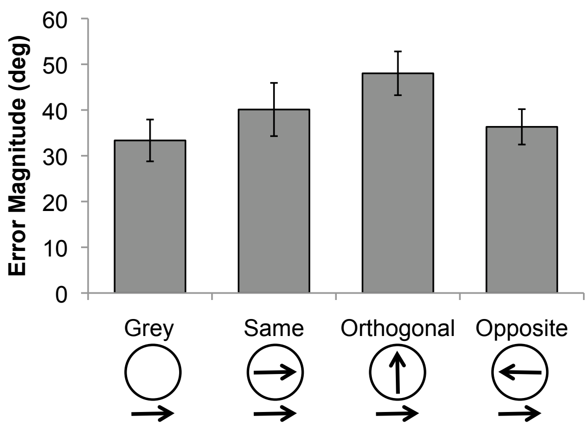


Figure 2.6. Error magnitude in direction reports for grey dots, same moving textures, orthogonal textures, and opposite moving textures in Experiment 2.3 when targets were probed. Error bars represent the standard error. Arrows below the circles indicate the object direction and arrows inside the circles indicate texture direction.

Chapter II Discussion

I investigated whether motion information is used in tracking by examining the effect of moving textures on direction reports. In Experiments 2.1 and 2.2, I found the errors in direction reports increased as the texture deviated further from the object motion. In Experiment 2.3, I showed that the large errors in direction reports for opposite texture were the result of losing the probed target. When direction reports for correctly tracked targets were examined, errors in direction reports were largest for targets with orthogonal texture. Further, these errors were biased in the same direction as the texture motion. These results are consistent with the motion hypothesis. Thus, I conclude that motion is used in the moment-to-moment tracking of objects.

The motion hypothesis and position hypothesis make very specific predictions about the effects of moving textures on direction reports. Both theories predict that direction reports for targets with same and opposite moving textures will be accurate; however, they make different predictions for direction reports for targets with orthogonal texture. The position hypothesis predicts direction reports for objects with orthogonal textures would be biased in the *opposite* direction of the texture motion. This bias is the result of the moving texture shifting the perceived location of the target in the direction of the texture motion. This shifted location is compared to the location of the target at the end of the trial to extrapolate direction from position information. The motion hypothesis predicts that direction reports for objects with orthogonal textures would be biased in the *same* direction as the texture motion. This bias may be caused by an integration of texture motion with the object motion to create a velocity representation used during tracking. My results support the motion hypothesis.

Processing of motion

How do moving textures influence direction reports? I have shown that orthogonal moving textures bias direction reports in the direction of the texture motion, demonstrating that texture motion is integrated with object motion during tracking. My stimuli consist of two types of motion, first-order motion and second-order motion (Cavanagh & Mather, 1989). First-order motion can be defined by changes in energy in Fourier space (Burr & Thompson, 2011). These stimuli are usually defined by spatiotemporal changes in luminance or color (Ledgeway & Smith, 1994). Second-order motion does not have any change in energy in Fourier space (Burr & Thompson, 2011). These stimuli are usually characterized by spatiotemporal changes in other characteristics, such as contrast or relative motion (Ledgeway & Smith, 1994). In my stimuli, the texture motion is defined by a change in luminance, so it is first-order; however, the mean luminance of the objects does not change. Thus, the object motion is second-order. I will discuss theories of motion perception to better understand how these two different types of motion may be combined during tracking.

Investigations of superimposed gratings, or plaids, have examined the mechanism for integrating motions overlapping in space to form a single percept of motion (Adelson & Movshon, 1982; Burr & Thompson, 2011; Yo & Wilson, 1992). Wilson and Kim (1994) showed the perceived direction of a plaid composed on one first-order grating and one second-order grating matched the vector sum solution. My results, however, are inconsistent with a vector sum solution for the integration of texture and object motion. A vector sum for objects with orthogonal textures would result in direction reports biased 63° towards the texture motion. This is not what I found. Direction reports were only biased toward the texture by about 9°. Thus, the vector sum mechanism cannot account for my results. A weighted vector sum could account for my results. Tse & Hsieh (2006) suggested object motion is weighted more heavily than local motion signals in the integration of motion. The task required attention to object motion, not texture motion. Thus, the object motion should be weighted more heavily in this task. Previous work has found that attention influences motion perception and may be responsible for determining the weighting of motion signals (Alais, & Blake, 1999; Lu, Liu, & Dosher, 2000; Raymond, 2000; Rees, Frith, & Lavie, 1997; Valdes-Sosa, Cobo, & Pinila, 1998). In a different task, perhaps one that requires attention to texture motion, it is possible that the texture motion would be weighted more heavily and create a larger bias in direction reports.

Models of motion perception are unclear as to how first-order and second-order motion are combined. Some models propose first-order and second-order motion are processed by the same mechanism (Cavanagh & Mather, 1989; Chubb & Sperling, 1988; Derrington, Allen, & Delicato, 2004; Hock & Gilroy, 2005; Smith, Snowden, & Milne, 1994), while others propose they are processed by different mechanisms (Anstis & Mackay, 1980; Ledgeway & Smith, 1995; Mather & West, 1993; Seiffert & Cavanagh, 1998). Lu & Sperling (2001) suggested there are three types of motion, each processed by a different mechanism. First-order motion and second-order motion are processed by different mechanisms and a third mechanism processes changes in salience. Attention influences motion perception (Lu et al., 2000; Rees et al., 1997; Valdes-Sosa et al., 1998) in the third order system (Lu & Sperling, 2001) by increasing the salience of attended motion. Research has been focused on understanding the mechanisms used to process different types of motion, but it has not examined how different types of motion are combined to create a coherent motion percept. Future research will need to determine how first-order motion and second-order motion are combined.

Instead of low-level motion signals, the tracking mechanism may use high-level motion derived from the internal signals used to guide attention (Cavanagh, 1992, 1995). These motion signals may be derived from the positions of features tracked by attention or from the signals that keep attention centered on the tracked object (Cavanagh, 1995). In other words, the motion signal is derived from a change in the focus of attention. This may be a change in the position of attention or in the displacement of attention. Tracking a target requires that the control process monitor the position of attention and compare it to the location of the target. As the target moves, attention must be repositioned. Signals from the control process could give rise to motion perception. High-level motion percepts may not be related to the motion percepts that arise from low-level motion mechanisms used to process first-order and second-order motion. At this time, it is not clear how moving textures would alter the perception of object motion created from the signal of the control process.

I have discussed low-level as well as high-level mechanisms of motion perception in relation to my findings. Attention is likely to mediate this process, either through a third-order motion system (Lu & Sperling, 2001) or through an active motion system used during tracking

(Cavanagh, 1992, 1995). Research on motion perception will need to examine how first-order and second-order motion are combined in the motion system before I can determine whether the direction percepts in my experiments are independent of low-level motion processes.

CHAPTER III

THE EFFECT OF SPEED ON TRACKING

Introduction

Moving objects have speed as well as direction. Thus far, this dissertation has found evidence that direction information is used during tracking, but it has not found evidence that speed information is used during tracking. Chapter II found that texture motion is combined with object motion, possibly through a weighted average, to form a representation of the object's direction. If texture motion and object motion are combined using a weighted average, moving textures would be expected to influence the perceived speed of objects. Opposite moving textures would be expected to reduce the perceived speed of the object, similar to backspin on a ball. Similarly, same moving textures may increase the perceived speed. In this chapter, I will investigate whether speed information is used during tracking and whether speed representations are affected by moving textures.

Tracking difficulty increases as the speed of the objects increases (Alvarez & Franconeri, 2007; Liu et al., 2005; Tombu & Seiffert, 2011), seeming to indicate a speed limit for tracking. However, when the speed of objects increases, a number of other factors in the MOT display also change, such as crowding and the distance travelled by an object. It has recently been proposed that the distance travelled by an object along with crowding, but not speed, limit tracking (Franconeri et al., 2010; Franconeri et al., 2008). Numerous studies have shown that tracking is more difficult in crowded displays (Alvarez & Franconeri, 2007; Intriligator & Cavanagh, 2001;

Pylyshyn, 2004; Shim et al., 2008; Tombu & Seiffert, 2011). In the typical MOT display, objects move within a framed region of space. In this display, objects get close to one another more often as their speed increases. One study manipulated speed while controlling for all other factors that affect tracking (Franconeri et al., 2010). In this study, each target was paired with a distractor. The pairs of dots rotated about their central point, so the amount of crowding did not change during tracking. The duration of the tracking period changed with the speed of the dots to control for differences in distance travelled during tracking. Tracking accuracy at high speeds did not differ from tracking accuracy at low speeds when the distance travelled by the dots was held constant. Although this study showed that speed does not limit tracking, it may not be a good experiment to determine if speed is used to predict the future locations of targets. The pairs of dots in this experiment changed their direction of rotation several times during tracking. Our previous work showed that less motion information is used when objects change direction unexpectedly (Seiffert & St.Clair, 2010). Speed may be used to predict the future locations of targets when the motion of objects is more predictable.

Studies of apparent motion percepts give reason to believe motion is used to predict the future locations of objects (Ramachandran & Anstis, 1983; Wertheimer, 1912). When two lights are flashed in alternation near one another, observers perceive motion between the lights (Burr & Thompson, 2011; Nijhawan, 1994; Wertheimer, 1912). The motion percept is affected by the spatial and temporal separation of the lights (Bowne, McKee, & Glaser, 1989; Castet, 1995). The apparent motion percept may be the result of an interpolation mechanism that fills in the locations between the two discrete target locations and an extrapolation mechanism that predicts the next location of the object (Hogendoorn et al., 2008). Shiori and colleagues (2000) provided evidence to this point using an attentive tracking task that required observers to attend to one direction of motion to resolve the apparent motion percept. In this study, two different arrangements of dots were presented sequentially to give the impression of dots rotating. The first arrangement of dots was presented, followed by a blank period, then the second arrangement of dots was presented. The direction of rotation was ambiguous in the display, but attention in the clockwise or counterclockwise direction guided motion perception. At the end of the tracking interval the screen blanked and a probe appeared a short time later. Observers rotated the probe to select the location where the target disappeared. The timing of the probe was manipulated to examine whether localization errors followed a linear prediction of the target's location. The reported target locations were consistent with the hypothesis that the locations between the discrete target locations were filled in using predictions from motion. When the probe was presented at the same time the screen blanked, people selected the location where the target disappeared. As the amount of time between when the screen blanked and the time the probe appeared increased, the amount of localization error in the direction of the target's trajectory increased in a manner consistent with a linear prediction of the target's location between the two discrete target locations.

Localization errors have also provided some evidence that speed information, as well as direction information, is used to track targets with continuous motion (Iordanescu et al., 2009). Observers tracked three targets, and at the end of the tracking interval, the objects disappeared. Observers used the mouse to select the location of disappearance of a randomly chosen target. The vector between the target's location of disappearance and the selected location was computed. Iordanescu and colleagues (2009) found that the direction of the response vector was tuned to the direction of the target and stronger direction tuning was associated with smaller localization errors. That is to say, people who showed evidence of using the target's direction of motion during tracking selected locations closer to the target's disappearance location. Further, they found that the speed of the target was associated with the size of the localization error. People selected locations further ahead in the target's trajectory when the target moved faster, consistent with the use of speed information during tracking. Taken together, these results show that both direction and speed may be used to predict the future locations of targets.

Here, I examined how moving textures influenced the use of speed information used during tracking. Experiments 3.1 and 3.2 examined localization errors after targets disappeared, to determine how moving textures influence speed information. The position hypothesis predicts localization errors will not be biased in any direction because motion information is not used during tracking. The motion hypothesis predicts people will select locations further ahead in the target's trajectory because motion information is used during tracking to predict the future locations of targets. These experiments showed that localization errors were biased in the direction of the target's trajectory, consistent with the predictions of the motion hypothesis. The results did not show any effect of the texture motion on localization errors, suggesting that moving textures do not affect the speed representations used during tracking. Our previous work showed that unexpected changes in direction reduced the use of motion information during tracking (Seiffert & St.Clair, 2010). Experiment 3.3 examined whether or not unexpected changes in speed reduce the use of motion information during tracking.

Experiment 3.1: Localization errors in MOT

Target localization errors have provided some evidence that speed, as well as direction, is used during tracking (Iordanescu et al., 2009). Experiment 3.1 used methods similar to

Iordanescu and colleagues (2009) to examine whether or not moving textures influence the speed information used during tracking. Stimuli were dots filled with solid color or moving texture, and participants reported the location where the target disappeared at the end of the tracking period. I compared the location reports to the location of disappearance, to determine how moving textures altered the motion information used during tracking. If targets with opposite moving texture are perceived as slower than objects with static texture, I expected to find smaller localization errors for targets with opposite moving texture. Similarly, if targets with same moving texture are perceived as faster than targets with static texture, I expected to find larger localization for same moving textures. If speed information is not used during tracking, as predicted by the position hypothesis, I expected people to select the location where the target disappeared, instead of selecting locations further ahead in the target's trajectory.

Participants

Fourteen paid subjects participated in this experiment, following the procedures defined for the protection of human participants by Vanderbilt University and the APA Code (2002).

Apparatus

The stimuli were generated and presented on a Mac Mini with a 17-in, LCD monitor with a refresh rate of 75 Hz and observers sat approximately 68cm from the display. Stimuli were produced by Matlab 7.5.0 (R2007b) for OS X version 10.5.5 and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) version 3.0.8.

Stimuli

Stimuli were 10 dots, presented on a black background, in an 11.8° X 9.2° white frame. Each dot was red, green, or yellow with the constraint that there be at least two dots of each color. Dots were either filled with solid color or a random-dot texture with a diameter of 0.73°. The initial positions of the dots were randomized with the constraint that dots did not overlap with each other or the frame's border. Dots travelled at 2.5°/sec and were permitted to overlap during the tracking period. Dots travelled in linear paths and bounced off the frame's borders by reflecting with an added amount of random jitter, between 6 and 11 angular degrees, so that the dots did not continue along their previous paths. On trials in which the dots were filled with texture, the texture was stationary or moved relative to the dot's direction of motion at twice the object speed, approximately 5°/sec. The texture of each dot moved in the same, orthogonal, or opposite direction relative to the dot's motion.

Procedure

Each participant completed one 60-minute session containing experimental trials and practice trials. A chinrest was used to stabilize the viewing distance at 68 cm and participants maintained fixation on a white cross, 0.51° X 0.51° presented in the center of the display. Each trial began with the presentation of 10 dots. Three target dots, one of each color, flashed for 2 sec. The targets stopped flashing and the dots moved for a randomly chosen amount of time between 4 and 8 seconds. At the end of the trial, all of the dots disappeared and an auditory target color was presented. Participants used the mouse to click on the disappearance location of the target matching the named color. If the named target was lost, participants were instructed to select a location outside of the rectangular tracking region. Participants initiated the next trial with a key press. Each condition was presented once during practice for a total of 5 practice trials. During the experimental session, each condition was presented 24 times for a total of 120 trials.

Data Analysis

The localization errors were measured as the vector from the location of the center of the target, when it disappeared, to the location of the mouse click. The magnitude of the localization error was the length of this vector. Participants were asked to click outside the tracking area to indicate they had lost the probed target. However, they may not have done so on every trial. Instead, they may have clicked on a random location in the tracking area. To eliminate these trials, localization errors beyond the 99th percentile were exclude. Direction errors were measured as the acute angle between the response location and the direction of the target. We computed the same direction-tuning index used by Iordanescu and colleagues (2009) to statistically verify differences in direction tuning between texture conditions. The direction-tuning index for each participant was defined as,

$$\text{Direction-tuning index} = \frac{\#\ \text{of direction errors between 90 and 180 degrees}}{\#\ \text{of direction errors between 0 and 90 degrees}}$$

A value of 0 indicates consistent direction tuning, i.e. all direction errors were in the same direction as the target direction. A value of 1 indicates inconsistent direction tuning, i.e. direction errors were evenly distributed in the same direction as the target direction and the opposite direction of the target direction.

Results and Discussion

Figure 3.1 shows the mean localization errors for solid colors, static textures, same moving texture, orthogonal texture and opposite moving texture. A repeated measures ANOVA revealed no effect of texture on the magnitude of the localization errors ($F(4, 52) = 1.52$, $p = .21$), suggesting that moving textures do not speed information. Another repeated measures ANOVA revealed no effect of texture on the direction index ($F(4, 52) = 1.88$, $p = .13$). One sample t-test comparing the direction index of each texture condition to 1 revealed that the direction indexes for same textures ($M = .71$, $t(13) = -3.22$, $p < .05$) and solid dots ($M = .63$, $t(13) = -3.80$, $p < .05$) were less than 1, indicating that motion is extrapolated in the direction of the target motion. No other direction indexes were significantly different from 1. Although motion information may be used to extrapolate the future locations of targets, moving textures do not affect localization errors.

I replicated the finding of Iordanescu and colleagues (2009), that the locations of targets are extrapolated in the targets' directions of motion for solid colored dots; however, I did not find any evidence that localization is affected by moving textures. It is possible that use of three different colored dots reduced dependence on motion during tracking. The use of different colored dots in the tracking display improves tracking accuracy compared to use of only one color (Makovski & Jiang, 2009). Color may have been used to help distinguish targets from distractors, reducing the need to use motion during tracking.

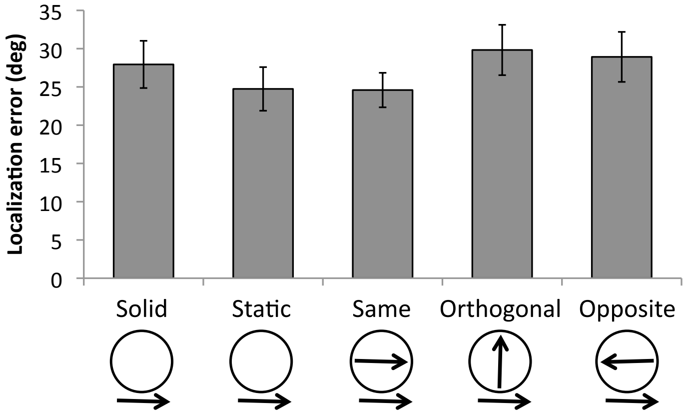


Figure 3.1. Mean localization errors for solid colored dots, static texture, same moving textures, orthogonal textures, and opposite moving textures in Experiment 3.1. Error bars represent the standard error. Arrows below the circles indicate the object direction and arrows inside the circles indicate texture direction.

Experiment 3.2: Localization errors in attentive tracking

Experiment 3.1 found moving textures do not affect the speed information used during tracking. However, this conclusion is based on a null result. It is possible that moving textures do affect speed information during tracking, but my methods could not detect the effect. Participants could select any location within the tracking area, which could result in highly variable responses. Moving textures may have a small affect on speed representations, but the effect was lost in the variability of responses. It is also possible that the color of the dots was used to overcome the texture effect. A target is most likely to be confused with a distractor when they are near one another. If a red target approached a green distractor, it would be possible to use color to distinguish the target from the distractor. This may reduce the need to make predictions from motion, or may compensate for prediction errors caused by the moving textures. Thus, the methods of Experiment 3.1 may not be able to detect changes in speed information caused by moving textures.

The attentive tracking task used by Shioiri and colleagues (2000) may be better suited for examining the affect of moving textures on the speed information used during tracking than the method used in Experiment 3.1. Response variability is reduced because responses are given by rotating a probe instead of selecting any location in the tracking area. The dots are also identical, so color cannot be used to aid tracking. The predictions for this experiment are the same as those for Experiment 3.1. If targets with opposite moving textures are perceived as slower than objects with static texture, I expected to find smaller localization errors for opposite moving textures. Similarly, if targets with same moving textures are perceived as faster than targets with static moving textures, I expected to find larger localization errors for same moving textures. If motion is not used during tracking, as predicted by the position hypothesis, I expected people to select the location where the target disappeared. To test whether the attentive tracking task is able to detect changes to speed information, I also examined the effect of contrast on localization errors. It has been shown that contrast influences speed perception (Anstis, 2003; Blakemore & Snowden, 1999; Stone & Thompson, 1992). Low contrast objects are perceived as moving slower than high contrast objects. Thus, I expected to find that localization errors are smaller for low contrast objects than for high contrast objects.

Participants

Two participants experienced in psychophysics participated in this experiment, following the procedures defined for the protection of human participants by Vanderbilt University and the APA Code (2002). One participant was the author and the other was experienced in psychophysical methods but naïve to the purpose of the experiment. The author was the only participant in the experiment that manipulated contrast.

Stimuli

The apparatus was the same as that in the previous experiment. The stimuli were 6 dots (1.2° diameter), arranged at equal distances around a circle (12.5° diameter), on a grey background (43.9 cd/m^2). The dots were presented in two different arrangements (Figure 3.2), so that when they alternated they produced ambiguous motion. Participants saw either clockwise or counterclockwise motion by tracking one of the dots with attention. The dots were either grey (71.7 cd/m^2) or filled with random-dot texture. On trials in which the dots were filled with texture, the texture was stationary or moved relative to the cued direction of motion at approximately 5°/sec. The texture of each dot moved in the same or opposite direction relative to the cued direction of motion. The probe was two black dots (0.84° diameter) on opposite sides of the fixation point 7° degrees apart. The experiment that manipulated contrast was identical, except the dots were always grey, and the contrast of the dots was manipulated instead of texture motion. The contrast of the dots was 10, 50, or 90% Michelson contrast. The color of the probe dots was red, so that they did not resemble the stimulus dots in the 90% contrast condition.

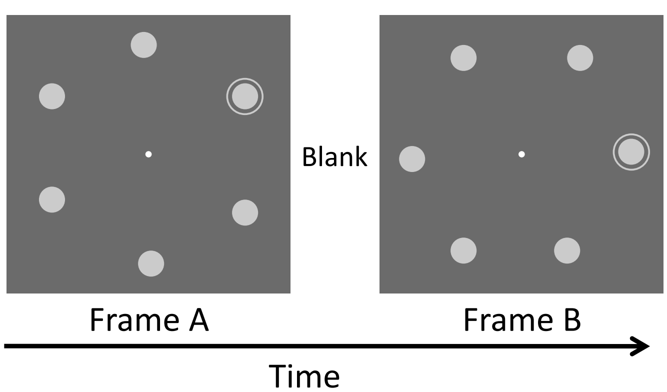


Figure 3.2. Illustration of the frame sequence during the cue period in Experiment 3.2. Dots were presented in one arrangement (Frame A) for 17 frames, the screen was blank for 1 frame, and then the dots were presented in another arrangement (Frame B) for 17 frames. The frame sequence was identical during the tracking period, except the cue ring was not presented around the target.

Procedure

Each participant completed four 90-minute sessions containing experimental trials. A chinrest was used to stabilize the viewing distance at 68 cm and participants maintained fixation on a white dot (0.25° in diameter), presented in the center of the display. Each trial began with the presentation of one arrangement of dots (Frame A) presented for 17 frames. The dots disappeared and the screen was blank, except for the fixation point, for 1 frame before the next arrangement of dots was presented for 17 frames (Frame B). The cue period was the first five alternations of the two frames. During this time, the target was circled by a grey (71.7 cd/m^2) ring, which led to the perception of motion in either the clockwise or counterclockwise direction. The cue ring disappeared and two alternations of the two frames were presented during the tracking period. The tracking period was short to reduce the likelihood of losing the target. At the end of the trial, the dots disappeared and the probe dots either appeared immediately or after 2, 4, 6, 8, 10, 12, 14 blank frames were presented (Figure 3.3). The probe dots were centered on a randomly chosen angle between 0 and 45 angular degrees from the location where the target disappeared. Participants imagined a perpendicular line extending from the probe dots. Using button presses, participants rotated the probe dots so that the imagined line pointed to the location where the target disappeared. Participants initiated the next trial with a key press. The texture condition remained the same during a block. The order of the texture conditions was determined for each participant using a Latin Square. Within a block, each probe onset condition appeared 15 times for a total of 120 trials. The procedure was the same for the contrast manipulation, except the participant completed 3 sessions, and the contrast of the dots was manipulated across blocks of trials.

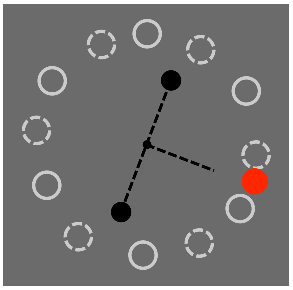


Figure 3.3. Illustration of the probe period in Experiment 3.2. The solid grey circles indicate the locations of the dots on Frame A. The dotted grey circles indicate the locations of the dots on Frame B. The two black dots appeared, and participants imagined a perpendicular line extending from the imagined line connecting the dots. The dotted lines were not present on the screen; they represent the lines imagined by the participant. The red dot represents the perceived location of the target at the time the probe appeared.

Results and Discussion

Figure 3.4 shows the localization errors for each texture condition for observers RS and SH. As the amount of time before the probe appeared increased, both observers selected locations further in the target's path. Linear regression was used to determine whether the responses matched predictions from continuous motion between the two discrete target locations for each condition. For observer RS the same texture R^2 = .93, the opposite texture R^2 = .87, the static texture R^2 = .92, and the solid grey R^2 = .94, indicating a linear model is a good fit to the data for each texture condition. The trends in the data were not consistent with the predictions for this experiment, indicating texture motion did not alter the speed information used during tracking. For observer SH the same texture R^2 = .87, the opposite texture R^2 = .67, the static texture R^2 = .91, and the solid grey R^2 = .74, indicating a linear model is a good fit to the data for each texture condition. The trends in the data were not consistent with the predictions for this experiment, indicating texture motion did not alter the speed information used during tacking. The results for both observers are consistent with the hypothesis that speed information is used during tracking to predict target locations. Further, they show that moving textures do not alter the speed information used in this task.

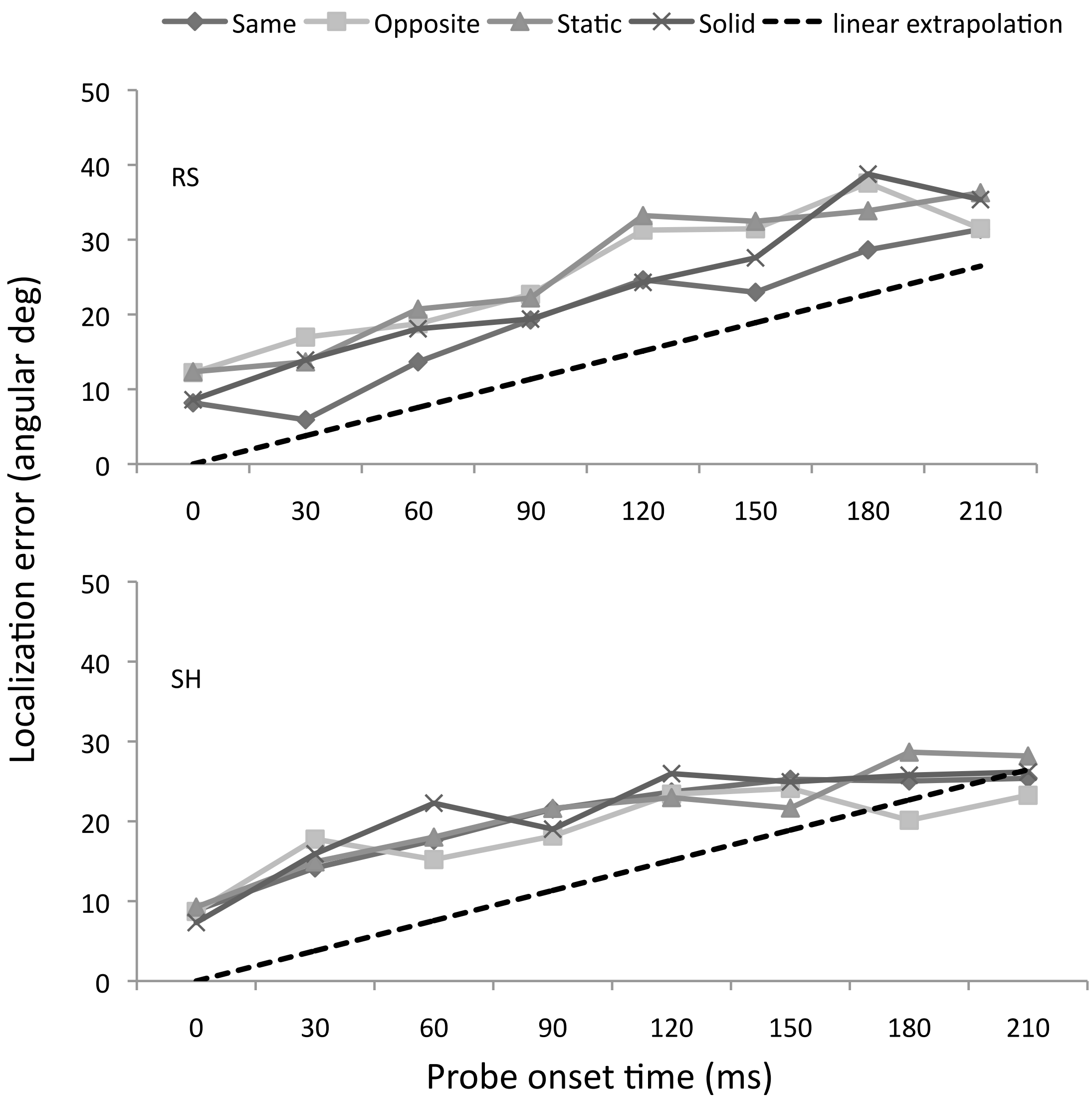


Figure 3.4. Localization errors as a function of probe time for solid colored dots, same moving texture, opposite moving texture, and static texture. The black dotted line indicates the trajectory of linear motion between the two discrete target locations.

Figure 3.5 shows the localization errors for each contrast condition. The observer selected locations further in the target's path as the amount of time before the probe appeared increased, as in the texture version of this experiment. Linear regression was used to determine whether the responses matched predictions from continuous motion between the two discrete target locations for each condition. For observer RS the low contrast R^2 = .97, the medium contrast R^2 = .97, and the high contrast R^2 = .74, indicating a linear model is a good fit to the data for each contrast condition. The trends in the data were not consistent with the predictions for this experiment, indicating contrast does not alter the speed information used during tracking. Contrast is known to effect speed perception (Anstis, 2003; Blakemore & Snowden, 1999; Stone & Thompson, 1992), but it did not affect localization errors in this experiment. The reason for this is unclear at this time, but these results indicate the attentive tracking task is not a good way to measure the use of speed information during tracking.

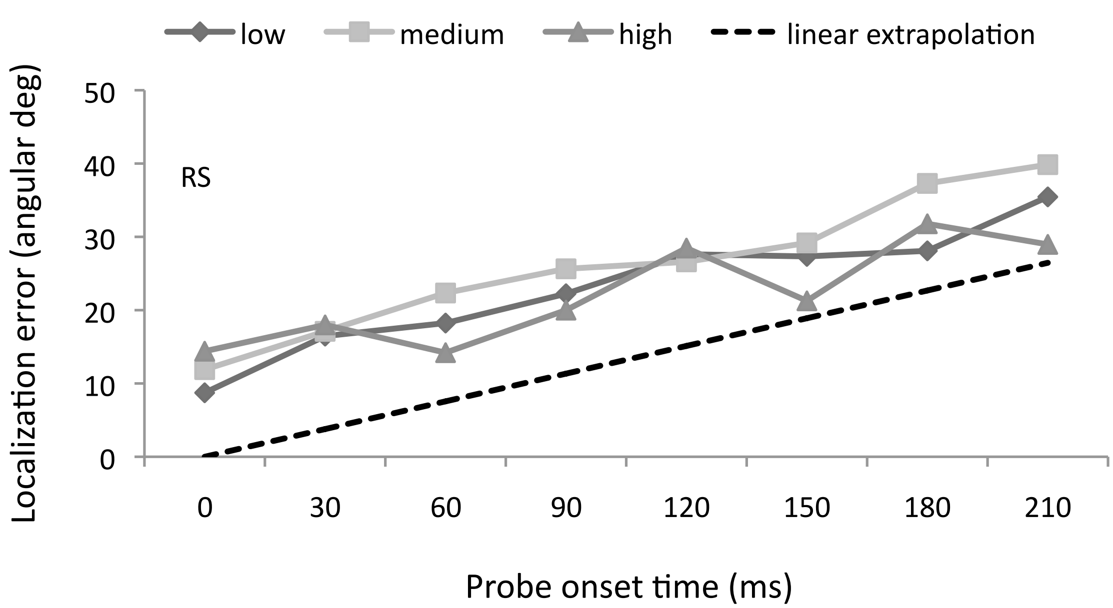


Figure 3.5. Localization errors as a function of probe time for low, medium, and high contrast dots. The black dotted line indicates the trajectory of linear motion between the two discrete target locations.

Experiment 3.3: Predictability of speed

Experiments 3.2 showed motion information is used during attentive tracking. The attentive tracking task used in these experiments differs in a number of ways from the MOT task. First, only one target was tracked. The use of motion during tracking may differ when only one target is tracked instead of multiple targets. Second, the direction of motion in the stimulus was ambiguous, requiring attentive tracking to perceive one direction of motion throughout the trial. Motion representations formed by attentive tracking may arise from a different mechanism than the motion representations formed by the low-level motion system that processes first-order motion (Cavanagh, 1992). Third, the dots travelled along a well-defined circular path, limiting the number of locations the target could appear. Experiment 3.1 used the typical MOT display but did not find any effect of moving textures on localization errors. However, the dots were not all the same color. Color may have been used to help distinguish targets from distractors, reducing the need to use motion information during tracking. Experiment 3.3 used the typical MOT display, without distinguishing colors, to examine whether the predictability of speed during tracking affects the use of motion. Our previous work showed that unexpected changes in direction reduced the effect of conflicting texture motion on tracking (Seiffert & St.Clair, 2010). We concluded that motion information is used less when objects move unpredictably. To my knowledge, no experiment has manipulated the predictability of speed during tracking. Here, I examined whether or not unexpected changes in speed also reduce the effect of texture motion on tracking. A reduced texture effect when objects change speed unexpectedly will be evidence that speed information is used during tracking.

Participants

Twelve participants from Vanderbilt University participated in the experiment for course credit, following the procedures defined for the protection of human participants by Vanderbilt University and the APA Code (2002).

Stimuli

The apparatus was the same as that in the previous experiment. Stimuli were 8 squares filled with random dot texture or solid grey color presented in a white frame filled with random-dot texture. The random-dot texture of the background was regenerated at the beginning of each trial and remained stationary throughout the trial. The frame was approximately 16° X 16° of visual angle, and each square was approximately 1.4° X 1.4°. Green square frames approximately 1.9° X 1.9° outlined the borders of the squares to designate targets. The initial positions of the squares were randomized with the constraint that squares did not overlap with each other or the frame's border. Squares travelled in linear paths and were permitted to overlap during the tracking period. Squares bounced off the frame's borders by reflecting with an added amount of random jitter, between 6 and 11 angular degrees. On every trial the squares began moving at 3.3°/sec and either kept the same speed throughout the trial or randomly changed speed 10 times during the tracking period. Squares changed speed by 0.5, 1.2, or 2°/sec. Squares sped up or slowed down with a probability of 0.5 with the caveat that they not go slower than 0.2°/sec or faster than 6.4°/sec. In the moving texture conditions, the texture of each square moved either in the same direction or the opposite direction relative to the square's trajectory at twice the object's speed.

Procedure

Each participant completed one 60-minute session, containing experimental trials and practice trials. The trial began with the presentation of 8 squares, each with a black border. The cues, green frames, were presented for 2 sec to designate 3 squares as targets. The cues and black borders were removed and a tone was presented to designate the beginning of the tracking interval. The squares moved for 4 seconds. At the end of the trial the black borders reappeared and the squares remained stationary while observers used the mouse to select the targets. Selected squares turned blue. After all 3 selections were made, the correct answer was shown in white and incorrect selections remained blue. After 2 sec, the next trial started automatically. At the end of each block the observers were shown their average percent correct for the block and encouraged to take a break. The observer pressed the spacebar to start the next block. During practice, five randomly selected conditions were presented for a total of 5 trials. During the experimental session, each condition was presented 3 times in each block. Three blocks were presented for a total of 9 repetitions per condition for each participant.

Results and Discussion

Figure 3.6 shows the tracking accuracy for solid grey squares, same moving texture, and opposite moving texture for each speed condition. A repeated measures ANOVA revealed a main effect of texture $F(2, 22) = 69.83$, $p < .05$. There was no main effect of speed change $F(3, 33) = 0.391$, $p = .760$ or interaction between texture condition and speed change, $F(6, 66) = 1.37$, $p = .241$. As in previous experiments, objects with opposite moving texture were more difficult to track than objects with same moving texture. The texture effect was unaffected by random changes in object speed.

Several explanations could account for why there was no affect of speed changes on tracking accuracy. First, the speed changes I used may not have been large enough to see an effect. The texture speed always moved at twice the object speed. As the texture speed increases the distance travelled by the texture on a single frame increases. The texture will not be perceived as moving when the texture moves too far on a single frame, placing an upper limit on the texture speed. To use larger changes in object speed, this limit would need to be exceeded. Second, there may have been too many or too few speed changes for each dot in a given trial. Objects changed speed about every 400ms. The amount of time needed to integrate motion during tracking is unclear (St.Clair, Huff, & Seiffert, 2010). Motion integration can be mediated by attention (Burr, Baldassi, Morrone, & Verghese, 2009) and can occur over short intervals of 100 to 500 ms, or long intervals of 3 seconds (Burr & Thompson, 2011; Morrone, Burr, & Vaina, 1995; Watamaniuk & Sekuler, 1992). Thus, it is unclear how to adjust the number of speed changes. Third, the large size of the targets may have made the task too easy. The targets were large in this experiment to allow for a wider range of texture speeds, thus allowing for a larger range of object speeds. Future research will manipulate these factors to better determine whether the predictability of speed alters the use of motion information during tracking.

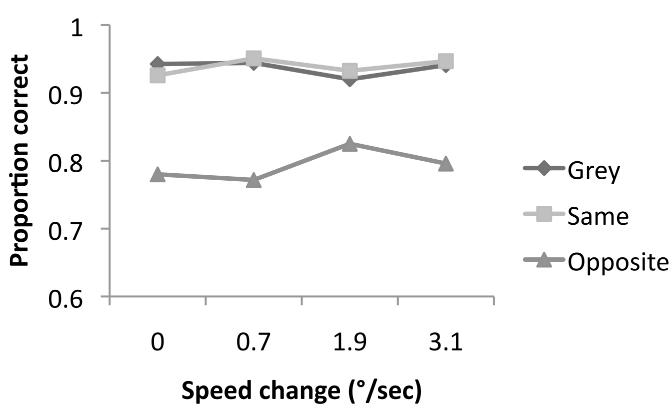


Figure 3.6. Mean tracking accuracy for grey squares, same moving textures and opposite moving for each speed change condition in Experiment 3.3. Error bars represent the standard error.

Chapter III Discussion

I investigated whether or not speed information is used during tracking by measuring localization errors and manipulating the predictability of speed during tracking. Experiment 3.1 and 3.2 showed localization errors are biased in the direction of the object motion. Neither experiment showed an effect of texture motion on localization errors. Experiment 3.2 also showed that localization errors in the attentive tracking task were not affected by contrast, even though contrast is known to affect the perceived speed of objects. Taken together, these results suggest motion information is used during tracking, but localization errors may not be a good way to measure speed perception during tracking. Experiment 3.3 showed unexpected changes in object speed did not affect tracking accuracy. The results of these studies do not support the position hypothesis. If participants relied solely on their memory of the last known target location during tracking, they would have correctly selected the disappearance location of the target in Experiments 3.1 and 3.2. Further, the localization errors would not have been biased in the direction of the target's motion and would not have followed the linear trajectory of motion between target locations in Experiment 3.2. This is the opposite of my results. Thus, my results do not support the position hypothesis.

Representational Momentum

Experiments 3.1 and 3.2 looked for evidence of that speed is used during tracking by examining localization errors. I suggested that forward displacements, or localization errors further in the target's trajectory, are evidence that speed information is used during tracking. However, other mechanisms are known to cause forward displacements. One such mechanism is representational momentum. When people are asked to remember the location of a moving object, they tend to remember the object in a location further along its trajectory (Freyd & Finke, 1984; Hubbard, 2005). Representational momentum may be beneficial because it allows for extrapolations of motions that cannot be tracked, such as objects moving behind an occluder, and allows us to anticipate the future locations of moving objects to guide action (Hubbard, 2005). Representational momentum may aid tracking by creating forward shifts in remembered locations of targets when attention switches between targets.

It may be argued that the position hypothesis can invoke representational momentum to explain my results. The methods of Experiment 3.1 are very similar to those used by Hubbard and Bharucha (1988) to study representational momentum. In their task only one target object was presented, whereas in the tracking task several objects were presented and there were multiple targets. Predictions about representational momentum are identical to the motion hypothesis's predictions about localization errors. However, representational momentum is a violation of the position hypothesis. The displacements of the target location associated with representational momentum indicate expectations about target motion (Hubbard, 2005). When a target is shown to bounce off the boundaries of a framed area, the direction of the displacement reflects and understanding of the bounce (Hubbard, 2005; Hubbard & Bharucha, 1988). When the target disappeared immediately after bouncing off the boundary, the target was displaced forward along the target's trajectory. If the target disappeared immediately before the bounce, the target was displaced backward, as if the target had bounced and changed direction. The position hypothesis is that motion is not used to track targets, so there should not by any expectations about the motion of targets. The expectations from motion that drive representational momentum are consistent with the motion hypothesis.

CHAPTER IV

THE EFFECT OF DISTRACTOR MOTION ON TRACKING

Introduction

The evidence that motion information is used during tracking has not distinguished between the use of target motion and the use of distractor motion. The goal of tracking is to be able to distinguish targets from distractors. As long as the targets can be identified, it may not be necessary to know anything about distractors. Thus, distractors may not be processed during tracking. It is possible that only targets are processed, so only the motion of targets is used during tracking. The alternative is that distractors are processed during tracking. “Crowding” refers to the finding that it is more difficult to identify targets when distractors are nearby (Levi, 2008; Pelli, Palomares, & Majaj, 2004; Tripathy & Cavanagh, 2002). When a target and distractor are close to one another, it may be useful to process information about the distractor, such as motion, to distinguish it from the target. Distractor motion may also be processed to predict when crowding events will occur. In this chapter, I investigated whether distractor motion is processed during tracking.

The visual index theory predicts distractor motion is not processed during tracking. The visual index theory claims pre-attentive indexes are assigned to targets as a way for attention to access the locations of targets (Pylyshyn, 1989; Pylyshyn, 2001, 2006; Pylyshyn & Storm, 1988). The indexes are only assigned to targets, so attention can only move to targets. A recent modification to the theory assigned inhibitory tags to distractors instead of indexes (Pylyshyn, 2006). The inhibitory tags do not provide access to the distractors. Rather, their function is to prevent attention from moving to these objects. Pylyshyn (2006) suggests that if all we had were inhibitory tags with no visual indexes, we would identify targets by finding objects without inhibitory tags. Thus, the visual index theory predicts that distractor motion will not be used during tracking.

Similar to the visual index theory, the multifocal theory of attention assumes distractor motion should not be processed during tracking. Rather, tracking resources should be assigned only to targets. Foci of attention are assigned to targets (Cavanagh & Alvarez, 2005). The foci of attention stay centered on targets throughout tracking. Distractors do not receive foci of attention, so they should not be processed. However, distractors may enter a focus of attention assigned to a target. When a distractor enters the focus of attention, it may be processed like the target. Thus, the multifocal theory of attention predicts only the motion of distractors near targets may be used during tracking.

The model of multiple identity tracking (MOMIT) predicts distractor motion may be processed to distinguish targets from distractors or to predict crowding (Oksama & Hyönä, 2008). Location-identity bindings are stored in memory and attention moves serially between targets to update these bindings. Attention moves to the location of the weakest target location-identity binding. If the target has moved from this location, attention moves to the nearest object. The features of nearest object are compared to the identity information of the target to determine if the object is the target. One feature that may be used in this comparison is motion. Target motion may be compared to the motion of the attended object. The location-identity binding is updated when the motions match, otherwise attention moves to the next nearest object. Thus, distractor motion may be processed to see if it matches the target motion information. The strength of the location-identity bindings is effected by crowding (Oksama & Hyönä, 2004). Crowding reduces the strength of the location-identity binding for the crowded target, increasing the likelihood that the crowded target will receive attention next. The motion of targets and distractors may be used to predict when a target will be crowded, so the strength of the location-identity binding can be adjusted. Thus, MOMIT predicts some distractor motion is used during tracking.

The probabilistic assignment model also predicts distractor motion is processed during tracking (Vul et al., 2009). The position and velocity of objects are used to predict their future locations. The predicted locations of all objects are compared to the locations of objects in the display. Each object receives an identity assignment of target or distractor. The combination of identity assignments that best matches the predicted locations of targets and distractors is assumed to be correct. All objects, including distractors, are given an identity. Thus, the probabilistic assignment model predicts that distractor motion is used during tracking.

Current theories of tracking predict that distractor motion is either processed during tracking (Cavanagh & Alvarez, 2005; Oksama & Hyönä, 2008; Vul et al., 2009), or inhibited (Pylyshyn, 2006). Researchers have measured responses to probes presented at different locations during tracking to examine the amount of processing distractors receive (Drew, McCollough, Horowitz, & Vogel, 2009; Flombaum, Scholl, & Pylyshyn, 2008; Pylyshyn, 2006). In the probe detection task, a low-contrast probe dot is flashed on a target, a distractor, or a stationary object during the tracking task. Participants press a button when they see the probe. The stationary object is used as a control, or baseline, for the detection of probes on objects. It is assumed that the stationary object is not part of the tracking task because it does not move. It is also assumed that probes are detected faster on attended objects than on unattended objects.

Results from investigations using this task are mixed. One investigation found that probe detection was worse for probes presented on distractors than for probes presented on stationary objects, consistent with the prediction that distractors are inhibited during tracking (Pylyshyn, 2006). However, another study found that probe detection on an occluder was higher when a target or distractor was behind the occluder than when nothing was behind the occluder (Flombaum et al., 2008). To know that a distractor is occluded, the distractor must be processed. A criticism of the probe detection task is that it creates a dual-task situation. Observers must track the targets and look for the probe, possibly changing how attention is distributed during tracking. One study did not ask participants to detect the probe. Instead, it measured the response the event-related potential (ERP) components believed to be associated with the distribution of spatial attention to the probe (Drew et al., 2009). The response of these components was highest for probes presented on targets, followed by probes presented on distractors, and was lowest for probes presented on stationary objects. These findings show distractors are processed less than targets during tracking, and do not support the prediction that distractors are inhibited. Results from probe detection studies are unclear as to whether distractors are processed during tracking. Some studies show distractors are inhibited (Pylyshyn, 2006) while others show distractors are processed (Drew et al., 2009; Flombaum et al., 2008).

Lavie's (1994, 1995) theory of attention may be able to explain why some studies show distractors are processed during tracking and others show distractors are not processed. Lavie’s theory predicts the amount of attention needed to perform a task will determine whether or not distractors are processed. If a task is easy and requires little attention, there will be attention left over to process distractors. If the task is difficult and requires a lot of attention, there will be no attention available to process distractors (Lavie & Cox, 1997; Rees et al., 1997). Support for

Lavie's theory has been found using fMRI to measure the activity level of MT, a motion processing area of the brain, to irrelevant motion presented during a high load and low load task (Rees et al., 1997). Participants were shown words and asked to press a button when they were uppercase (low load) or when they were bisyllabic (high load). In addition to the word, irrelevant motion was presented. Consistent with the predictions of Lavie's theory, the researchers found strong activation of MT in the low load, but not the high load condition. The irrelevant motion was only processed in the low load condition. Lavie's theory predicts distractors are only processed during tracking when the tracking load is low. In Pylyshyn's (2006) study that found distractors were not processed during tracking, participants tracked 4 targets, a high tracking load. In the ERP study that found distractors were processed, participants only tracked 2 targets (Drew et al., 2009). Attentional resources may be available to process distractors when participants track 2 targets, but not when they track 4 targets.

In summary, the visual index theory predicts distractors arenot be processed during tracking, while the other theories of tracking predict distractors may be processed. The multifocal theory of attention predicts distractors are only processed when they crowd targets. Lavie's theory of attention predicts distractors are processed when the tracking load is low, so enough that attentional resources are available to process distractors. A potential concern with using responses to a probe as a measure of distractor processing is that the flash of the probe may draw attention to objects that would otherwise not be attended. This is a concern even when the probe is irrelevant to the task. Instead of using the probe task to measure distractor processing, I measured the amount of distractor motion used during tracking. Our previous work demonstrated a texture effect in tracking (St.Clair et al., 2010). The texture effect refers to the finding that tracking accuracy is lower for objects with opposite moving texture than for objects with same moving texture. Experiment 4.1 examined whether or not distractor motion is used during tracking by manipulating the texture motion on targets separately from the texture motion on distractors. A texture effect for distractors was found, demonstrating distractor motion is used during tracking. Experiment 4.2 tested the prediction that only distractors near targets are processed by examining the effect of crowding on the distractor texture effect. Experiment 4.3 tested the prediction that distractors are processed less as the tracking load increases by measuring changes in the distractor texture effect with different tracking loads.

Experiment 4.1: Distractor motion in tracking

Our previous work showed that motion information is used during tracking, but it did not discriminate between target motion and distractor motion (St.Clair et al., 2010). Experiment 4.1 used the same textured stimuli that were used in our previous work, but manipulated the texture motion on distractors independently of the texture motion on targets to determine whether or not distractor motion is used during tracking. The texture could either move in the same direction as the object or the opposite direction of the object, for a total of four conditions: 1) targets had same moving texture and distractors had same moving texture, 2) targets had same moving texture and distractors had opposite moving texture, 3) targets had opposite moving texture and distractors had same moving texture, or 4) targets had opposite moving texture and distractors had opposite moving texture. If distractor motion is used during tracking, I expected to find that tracking accuracy is lower when distractors have opposite moving texture compared to when distractors have same moving texture.

Participants

Nineteen paid subjects participated in this experiment, following the procedures defined for the protection of human participants by Vanderbilt University and the APA Code (2002).

Apparatus

The stimuli were generated and presented on a Mac Mini with a 17-in, LCD monitor with a refresh rate of 75 Hz and observers sat approximately 60cm from the display. Stimuli were produced by Matlab 7.5.0 (R2007b) for OS X version 10.5.5 and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) version 3.0.8.

Stimuli

Stimuli were 10 squares filled with random dot texture presented in a white frame filled with random-dot texture. The random-dot texture of the background was regenerated at the beginning of each trial and remained stationary throughout the trial. The frame was approximately 16° X 17° visual angle. Each square was 1.0° X 1.0° visual angle. The initial positions of the squares were randomized with the constraint that squares did not overlap with each other or the frame's border. Green frames 1.2° X 1.2° in diameter outlined the borders of the squares to designate targets. Squares travelled at approximately 2.5°/sec and were permitted to overlap during the tracking period. Squares travelled in linear paths and bounced off the frame's borders by reflecting with an added amount of random jitter, between 6 and 11 angular degrees. The texture moved relative to the square's direction of motion at twice the object speed, approximately 5°/sec. The texture of each square moved in the same direction or the opposite direction relative to the square's trajectory. Four texture conditions were used: all squares had same moving texture, all squares had opposite moving texture, targets had same moving texture and distractors had opposite moving texture, and targets had opposite moving texture and distractors had same moving texture.

Procedure

Each participant completed one 60-minute session containing experimental trials and practice trials. Each trial began with the presentation of 10 squares, each with a black border. The cues, green rings, were presented for 2 sec to designate 3 squares as targets. The cues and black borders were removed and then a tone was presented to designate the beginning of the tracking interval. The squares moved for 6.7 seconds. At the end of the trial, the black borders reappeared and the squares remained stationary. Participants used the mouse to select the targets. Selected squares turned blue. After all 3 selections were made, the correct answer was shown in white. Incorrect selections remained blue. At the end of each block, participants were encouraged to take a break. During practice, each condition was presented once, for a total of 4 trials. During the experimental session, each condition was presented 4 times in each block. Five blocks were presented for a total of 20 repetitions per condition for each participant.

Data Analysis

I measured the texture effect for targets and distractors independently to determine if distractor motion is used during tracking. The texture effect is the difference in tracking accuracy for objects with same moving textures and objects with opposite moving textures. To measure tracking accuracy when targets had same moving texture, I computed the average tracking accuracy when targets had same moving texture and distractors had either same moving or opposite moving texture. To measure tracking accuracy when targets had opposite moving texture, I computed the average tracking accuracy when targets had opposite moving texture and distractors had either same moving or opposite moving texture. The texture effect for targets was computed by subtracting the average tracking accuracy when targets had opposite moving texture from the average tracking accuracy when targets had same moving textures. The texture effect for distractors was computed in a similar manner. To measure tracking accuracy when distractors had same moving texture, I computed the average tracking accuracy when distractors had same moving texture and targets had either same moving or opposite moving texture. To measure tracking accuracy when distractors had opposite moving texture, I computed the average tracking accuracy when distractors had opposite moving texture and targets had either same moving or opposite moving texture. The texture effect for distractors was computed by subtracting the average tracking accuracy when distractors had opposite moving texture from the average tracking accuracy when distractors had same moving textures. Positive texture effect values indicate higher tracking accuracy for objects with same moving texture than for objects with opposite moving texture, as was found in our previous work (St.Clair et al., 2010).

Results and Discussion

Figure 4.1 shows the texture effect for targets and distractors. One-sample t-tests revealed a significant texture effect for targets ($M = .18$; $t(18) = 11.13$, $p < .05$) and distractors ($M = .05$; $t(18) = 3.98$, $p < .05$). Target motion and distractor motion are used during tracking. Further, the target texture effect was larger than the distractor texture effect, $t(18) = 6.87$, $p < .05$, revealing that target motion is used more than distractor motion during tracking. This finding that distractor motion is used during tracking is inconsistent with the prediction of the visual index theory that distractors are not processed during tracking.

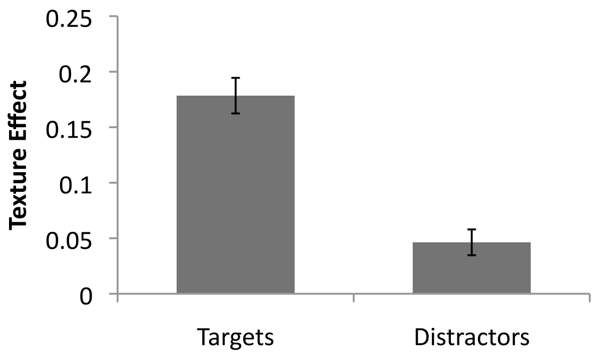


Figure 4.1. The texture effect for targets and distractors in Experiment 4.1. Error bars represent the standard error.

Experiment 4.2: Distractor motion and crowding

The motion of distractors may only be processed when distractors are near targets. The multifocal theory of attention makes this prediction because distractors enter the focus of attention centered on a target when they get too close to a target (Cavanagh & Alvarez, 2005). MOMIT makes this prediction because attention processes the object closes to the last known location of the target (Oksama & Hyönä, 2008). The motion of that object may be processed to determine whether it matches the motion of the target. Crowding could account for why distractor motion was used less than target motion in the previous experiment. Target motion may have been processed throughout the tracking period, whereas distractor motion may have only been processed when a distractor was near a target. Experiment 4.2 manipulated the level of crowding to determine whether or not distractor processing increases as crowding increases.

Participants

Thirteen paid subjects participated in this experiment, following the procedures defined for the protection of human participants by Vanderbilt University and the APA Code (2002).

Methods

The apparatus and procedure were the same as that in the previous experiment. The stimuli were also the same except the squares were smaller (0.7° X 0.7°), as was the size of the cue (0.8° X 0.8°). The motion of the dots also differed as a result of the crowding manipulation. The maximum proximity of dots to one another was 0, 0.5, 1, or 1.5 times the size of the dots (0°, 0.35°, 0.7°, and 1.1°, respectively). When two dots reached the proximity limit, they reversed direction. This manipulation confounds crowding and the number of times a dot changes direction. As the proximity limit between dots increases, the number of direction changes increases. Our previous work showed that changes in direction reduce the texture effect (Seiffert & St.Clair, 2010). To ensure that the number of direction changes did not differ between conditions, dots randomly reversed direction so that there was an average of 9 direction changes per dot in a given trial. During practice, 5 randomly chosen conditions were presented for a total of 5 trials. During the experimental session, each condition was presented 2 times in each block. Four blocks were presented for a total of 8 repetitions per condition for each participant.

Results and Discussion

Figure 4.2 shows the texture effect for targets and distractors for each level of crowding. A repeated measures ANOVA revealed a significant effect of crowding on tracking, $F(3, 36) = 13.05$, $p < .05$, replicating previous research that tracking accuracy declines as crowding increases (Alvarez & Franconeri, 2007; Intriligator & Cavanagh, 2001; Pylyshyn, 2004; Shim et al., 2008). As in the last experiment, the texture effect was significantly larger for targets than distractors, $F(1, 12) = 28.03$, $p < .05$. There was also a significant interaction between the texture effect for targets and distractors and crowding, $F(3, 36) = 4.05$, $p < .05$. Figure 4.2 shows the direction of the texture effect differs in direction between crowding conditions, as well as between targets and distractors. Positive values indicate objects with same moving texture were tracked better than objects with opposite moving texture, replicating Experiment 4.1. However, negative values indicate objects with same moving texture were tracked worse than objects with opposite moving texture, an unexpected result.

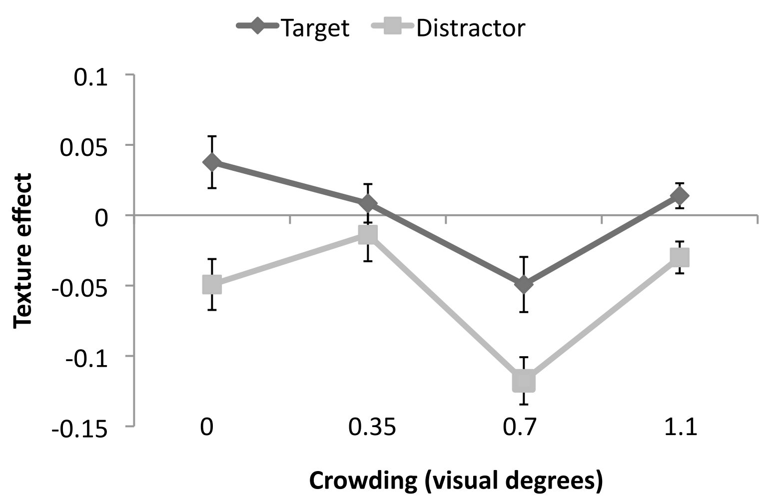


Figure 4.2. The texture effect for targets and distractors for each level of crowding in Experiment 4.2. Error bars represent the standard error.

One reason for the change in the texture effect observed in this experiment is that objects changed direction frequently. As crowding increased, the number of direction changes increased to keep targets and distractors a minimum distance apart. The number of direction changes was controlled across levels of crowding by adding random direction changes during tracking. This resulted in an average of 9 direction changes for each dot per trial. Prior work has found that the texture effect is reduced when objects change direction unexpectedly (Seiffert & St.Clair, 2010). The unexpected changes in direction may have negated the texture effect in this experiment. To examine this possibility, I compared tracking accuracy when all objects had same moving textures to tracking accuracy when all objects had opposite moving texture for the lowest level of crowding. A paired t-test revealed that opposite moving (M =.82) textures were tracked as well as same moving textures (M = .81; $t(12) = -0.43$, $p > .05$), supporting the conclusion that the direction changes in this experiment eliminated the texture effect. Because I did not find a texture effect, I cannot draw conclusions about the effect of crowding on the use of target or distractor motion during tracking.

Experiment 4.3: Distractor motion and tracking load

Lavie's (1994, 1995) theory of attention predicts that the processing of distractors is contingent on the tracking load, because tracking draws on a limited resource. When the tracking load is sufficiently high, all of these resources are allocated to targets. However, when the tracking load does not demand all of these resources for targets, the remaining resources may be used to process distractors. This would predict a larger texture effect for distractors at low tracking loads than at high tracking loads. Experiment 4.3 tested this prediction by examining changes in the distractor texture effect for tracking loads of 2, 3, 4, and 5 targets.

Participants

Twelve paid subjects participated in this experiment, following the procedures defined for the protection of human participants by Vanderbilt University and the APA Code (2002).

Methods

The apparatus and procedure were the same as Experiment 4.1. The stimuli were also the same as in Experiment 4.1, except the squares moved slower (approximately 1.1°/sec) for 4 sec. In addition to the conditions used in Experiment 4.1, the number of targets varied. Participants tracked 2, 3, 4 or 5 targets. During practice, 4 randomly chosen conditions were presented. During the experimental session, each condition was presented 2 times in each block. Five blocks were presented for a total of 10 repetitions per condition for each participant.

Results and Discussion

Figure 4.3 shows the texture effect for targets and distractors for tracking loads of 2, 3, 4, and 5 targets. A repeated measures ANOVA revealed a significant effect of target load on tracking, $F(3, 33) = 3.12$, $p < .05$, replicating previous research that tracking accuracy declines as the tracking load increases (Intriligator & Cavanagh, 2001; Pylyshyn, 2006; Pylyshyn & Storm, 1988; Scholl & Pylyshyn, 1999; Scholl et al., 2001; Sears & Pylyshyn, 2000; Yantis, 1992). The texture effect was no different for targets than for distractors, $F(1, 11) = 31.83$, $p > .05$, and there was no interaction with target load, $F(3, 33) = 0.87$, $p > .05$. The use of distractor motion did not change with tracking load. This finding does not support the prediction from Lavie's (1994, 1995) theory that distractors are processed more at low tracking loads than at high tracking loads. Rather, distractors processing is the same for high and low tracking loads. Tracking accuracy declines at high loads so it is possible that distractors are processed at high loads because they are mistaken for targets. A distractor mistaken for a target is tracked, and thus processed during tracking. The texture effect uses tracking accuracy to determine whether motion is used during tracking. Another measure, not dependent on tracking accuracy, will need to be used to determine whether distractor motion is used at high tracking loads when all targets are tracked correctly.

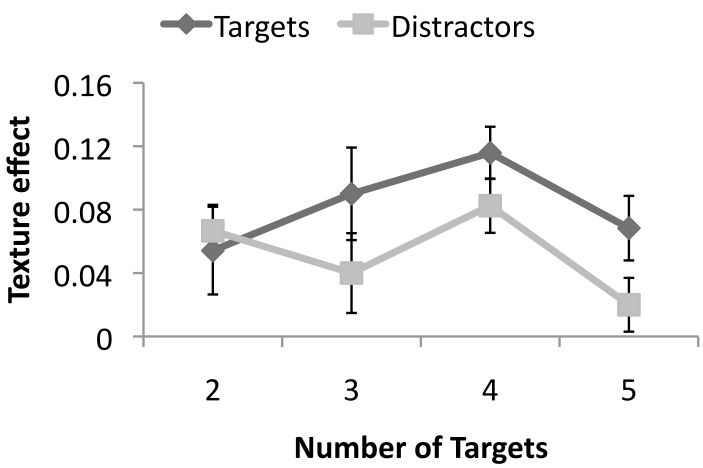


Figure 4.3. Size of the texture effect for targets (black line) and distractors (grey line) for tracking loads of 2, 3, 4 and 5 targets in Experiment 4.3. Error bars represent the standard error.

Chapter IV Discussion

I investigated whether distractor motion is used in tracking by manipulating the direction of texture motion on distractors independent of the texture motion on targets.

In Experiments 4.1 and 4.3 I found a texture effect for targets and distractors. Tracking accuracy was worse when distractors had opposite moving texture than when they had same moving texture, regardless of the direction of the texture motion on targets. This finding demonstrates distractor motion is used during tracking. Experiment 4.3 showed that the texture effect for targets and distractors was unaffected by tracking load, suggesting that distractor motion is not used more at low tracking loads than at high tracking loads. Experiment 4.2 examined the effect of crowding on the use of motion during tracking. This experiment replicated the finding that increased crowding reduces tracking accuracy, but it did not find a texture effect. Because a texture effect was not found, it was not possible to examine how changes in crowding effect use of distractor motion during tracking. Taken together, these findings support the conclusion that distractor motion is used during tracking.

Why process distractors?

The experiments in this chapter show that distractor motion is processed during tracking, adding to previous evidence that distractors are processed during tracking (Drew et al., 2009; Flombaum et al., 2008; Pylyshyn, 2006). Experiment 4.1 showed target motion is processed more than distractor motion during tracking, consistent with previous findings that targets are processed more than distractors (Bettencourt & Somers, 2009; Drew et al., 2009; Pylyshyn, 2006). Previous studies measured responses to a probe flashed during tracking to examine whether distractors are processed during tracking (Drew et al., 2009; Flombaum et al., 2008; Pylyshyn, 2006). A heavy criticism of these studies is that the presence of the probe alters how people do the tracking task. Here, I found evidence of distractor processing without changing the nature of the tracking task. These results beg the question, why process distracting information? Why not devote all of our tracking resources to targets? We may process distractors because we cannot prevent them from being processed, or we may process them because it helps us distinguish them from targets.

Preventing distractors from being processed may draw on limited resources (Bettencourt & Somers, 2009; Cavanagh, 2011; Hickey, Di Lollo, & McDonald, 2008), and there may not always be enough resources available to prevent all distracting information from being processed. The multifocal theory of attention assumes everything in the foci of attention is processed (Cavanagh & Alvarez, 2005). The foci are centered on targets, but distractors may enter the foci as they near targets. When a distractor enters the focus of attention, it is processed and may be confused for a target (Alvarez & Franconeri, 2007; Intriligator & Cavanagh, 2001; Oksama & Hyönä, 2004; Pylyshyn, 2004; Sears & Pylyshyn, 2000). The focus of attention must shrink to prevent distractors from entering the focus of attention. Shrinking the focus of attention requires additional resources that may not always be available, as when tracking a high number of targets. Unlike Lavie's theory, this would predict that distractors are processed more at high tracking loads. Experiment 4.3 does not support this prediction because there was no change in distractor processing as tracking load increased. All available resources may be used during tracking. When all of the resources are not used to reduce the resolution of attention, the remaining resources may be used to process distractors. Distractors may be processed at low tracking loads because tracking the targets does not use all the available resources, leaving some resources for processing distractors. However, at high tracking loads distractors may be processed because attentional resources cannot suppress distractors by reducing the resolution of attention.

Processing distractor motion may be beneficial because it allows us to predict crowding events and adds to the information we can use to distinguish targets from distractors. The probabilistic assignment model uses predictions from position and motion information to assign identities to all objects, including distractors (Vul et al., 2009). Alternatively, predictions about the future locations of targets and distractors may be used to predict crowding events, so crowded targets receive more tracking resources than targets that are not crowded (Bettencourt & Somers, 2009). They could also be used to determine which target should receive priority for attention. The location-identity bindings proposed by MOMIT are weaker for crowded targets than for targets that are not crowded. This weaker location-identity binding increases the likelihood that attention will move to the crowded target. Adjusting the strength of the location-identity binding to account for crowding may rely on predictions about where targets and distractors are going. MOMIT may also process distractors to determine that they are not targets. Attention moves to the location of the weakest target-location binding. If there is no object at this location, it moves to the closest object. Identity information is used to determine if the object is a target. If motion is the only information that can be used to identify a target, it may be used to determine if the attended object is the target. This means the motion of the attended object is processed to determine if it matches the motion of the target. If the motions match, the object is identified as a target. If the motions do not match, attention moves to the nearest object. Every instance of a failed match is an instance when distractor motion is processed. The use of motion as a feature or for prediction during tracking will be discussed in more detail in the General Discussion.

CHAPTER V

GENERAL DISCUSSION

The purpose of this investigation was to determine whether or not motion is used in the moment-to-moment tracking of multiple objects. The position hypothesis is that objects are tracked using only position information. The motion hypothesis is that motion is also used during tracking, possibly to predict the future locations of targets. I tested these hypotheses in a number of ways (Table 5.1). First, I examined whether moving textures influence the representations of the targets' directions of motion used during tracking. Direction reports for correctly tracked targets were biased in the direction of the texture motion, providing evidence that texture motion is integrated with the motion of the object during tracking. Second, I examined whether or notmoving textures influenced extrapolation during tracking. The positions of targets were extrapolated, but this extrapolation was unaffected by changes in texture direction. Similarly, the extrapolation was unaffected by changes in object contrast, a factor known to influence speed perception (Anstis, 2003; Blakemore & Snowden, 1999; Stone & Thompson, 1992). Third, I examined whether distractor motion is used during tracking. Tracking was impaired when distractors had conflicting texture, regardless of the direction of the texture motion on the targets, consistent with the prediction that distractor motion is used during tracking. The use of distractor motion persisted when participants tracked up to five targets. The examination of the effect of crowding on the use of distractor motion was inconclusive. Taken together, these findings demonstrate that the motion of targets and distractors is used during tracking. These results are not consistent with the position hypothesis of tracking. Instead, support the motion hypothesis.

Experiment	Method	Important Result
2.1	Participants reported the direction of a randomly chosen object at the end of tracking for different texture motions.	Direction reports were biased in the direction of the texture motion.
2.2	Same methods as Exp. 2.1, except only targets were probed.	Direction reports were biased in the direction of the texture motion, even when the target was tracked correctly.
2.3	Same methods as Exp. 2.1, but visual feedback was given.	Direction reports were biased in the direction of the texture motion, even when participants received feedback.
3.1	Methods were similar to Iordanescu, et al. (2009). Participants selected the location where a target disappeared for different texture motions.	Participants selected locations in the same direction as the target's trajectory. The size of localization errors was not affected by texture motion.
3.2	Methods were similar to Shioiri, et al. (2001). Participants selected the location where the target disappeared in an attentive tracking task for different texture motions. In an identical experiment, the contrast of the objects was manipulated.	Localization errors followed a linear trajectory of the object motion but were not affected by texture motion or changes in contrast.
3.3	Participants tracked targets that randomly changed speed for different texture conditions.	Random changes in object speed did not affect tracking accuracy.
4.1	Texture motion was manipulated independently for targets and distractors in an MOT task.	A texture effect was demonstrated for targets and distractors.
4.2	Same methods as Exp. 4.1, except crowding was also manipulated.	The texture effect for distractors was not affected by changes in crowding.
4.3	Same methods as Exp. 4.1, except the number of target was manipulated.	The texture effect for distractors did not change with tracking load.

Table 5.1. Summary of the methods and results for each experiment in this dissertation.

When is motion used during tracking?

How can my finding that we use motion during tracking be reconciled with the findings that suggest motion is not used during tracking? Many studies that examined the use of motion during tracking showed motion is not used to predict the future locations of targets (Fencsik et al., 2007; Franconeri et al., 2012; Keane & Pylyshyn, 2006). It has even been suggested that the amount of crowding and the distance travelled by objects, not the speed of the objects, limits tracking (Franconeri et al., 2010; Franconeri et al., 2008). Our previous work also suggests that motion may not always be used during tracking (Seiffert & St.Clair, 2010). Here, I will review these studies to determine when motion is used during tracking.

Support for the position hypothesis relies heavily on a variant of the multiple object tracking (MOT) task in which the objects disappear briefly during tracking (Fencsik et al., 2007; Franconeri et al., 2012; Keane & Pylyshyn, 2006). In one variant of this task, the objects either continued moving or paused while they were invisible. Targets were recovered better when they paused than when they kept moving (Fencsik et al., 2007; Keane & Pylyshyn, 2006), showing that motion was not used to predict where the targets would reappear. In a similar study, objects moved behind vertical bars during tracking (Franconeri et al., 2012). While they were occluded, the trajectory of the objects either remained the same as before they were occluded, or changed by 30° or 60°. Objects that changed direction were tracked as well as objects that did not change direction. The direction of the objects was not used to predict where the objects would reappear. Matching direction of motion before occlusion to the direction of motion after occlusion was not necessary to recover the targets. The finding that motion is not used to recover targets must be reconciled with the finding of this dissertation, that motion is used during tracking.

One important difference between my studies and the studies that have found motion is not used to recover targets during tracking is the visibility of the objects. In my studies, the objects are always visible, whereas the objects disappear briefly in examinations of target recovery. Recovering objects that disappear may use a different mechanism than tracking objects that remain visible. There is evidence from studies of the oculomotor system that suggest the visual system treats invisible objects differently than visible objects (Barnes, 2008; Becker & Fuchs, 1985; Ilg, 2008). The velocity of smooth pursuit eye movements is only consistent while the target motion is present or implied by the stimulus. The velocity of the smooth pursuit eye movements quickly drops to 60% of the target's velocity when the target disappears (Becker & Fuchs, 1985). Studies of apparent motion have examined motion percepts when objects briefly disappear. In a typical apparent motion display an object is presented briefly at one location, disappears for a short amount of time, and is then presented briefly at another location. When multiple objects are presented in the apparent motion display, the visual system must determine which object went where. In a display like the one depicted in Figure 5.1, the dots could be perceived moving horizontally or vertically. Because the distance between the vertical positions is less than the distance between the horizontal positions, vertical motion is perceived (Burt & Sperling, 1981; Navon, 1976; Scholl, 2007). This is similar to knowing the last location of the target during tracking and assuming the dot nearest that location is the target. A proximity rule, like the one used to resolve apparent motion, maybe be used to track targets that disappear during tracking, but not to track objects that remain visible. This could result in the use of position information to recover targets that are temporarily invisible and the use of motion information to track targets that are visible.

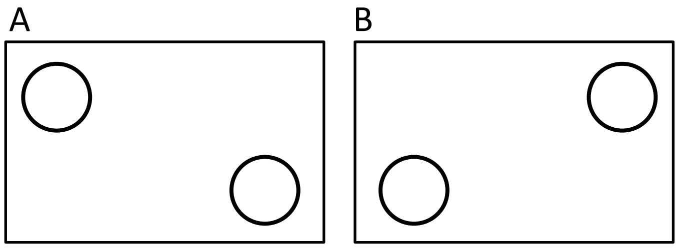


Figure 5.1. Illustration of an apparent motion display with two objects. Frame A is flashed briefly and then frame B is flashed briefly. The resulting percept is of the two dots moving vertically.

The other line of evidence favoring the position hypothesis suggests that speed does not limit tracking (Franconeri et al., 2010). Instead, increases in object speed increase the number of crowding events that occur during the tracking period. When crowding was controlled, the distance the target travelled, not the speed of the target, affected tracking accuracy. The finding that distance travelled, not speed, limits tracking may be a product of the stimulus motion used in the experiment (Franconeri et al., 2010). A target was paired with a distractor and the pair of dots rotated about a local point, randomly changing direction. Our previous work showed random changes in direction reduced the use of motion information during tracking (Seiffert & St.Clair, 2010). The pairs of dots changed direction unexpectedly throughout the trial, making the motion of the dots unpredictable. If the tracking mechanism tried to use motion information to predict the future locations of the targets, the prediction would be wrong when the dots changed direction, leading to a tracking error. Thus, the tracking mechanism may have limited the use of motion information in this tracking task and relied more heavily on position information.

Investigations of the use of motion during tracking have found that sometimes motion is used during tracking and sometimes only position information is used during tracking. When motion information is not available or changes unexpectedly, tracking may rely solely on position information. Other lines of research have proposed that the use of motion information is contingent on task demands (Thurman & Grossman, 2008). When available, motion is used to make discriminations. However, when static images are presented, other information is used to make discriminations, such as form. The same may be true for multiple object tracking. Motion is used during tracking when it is available.

Theories of MOT

Any theory of tracking must account for the finding that target motion and distractor motion are used during tracking. Many of the current theories of tracking are unclear as to how motion information may be used during tracking. Here, I will review current theories of tracking and suggest ways that they could modified to better account for my findings. This discussion will reveal that there are two possible uses for motion information during tracking. One possibility is that motion information is used to predict the future locations of targets and distractors. The other possibility is that motion information is used as a feature to distinguish between targets and distractors.

The visual index theory (or FINST theory) uses the spatial location of objects to track targets (Pylyshyn, 1989; Pylyshyn, 2001, 2006; Pylyshyn & Storm, 1988). Each target is assigned a unique mental index that serves as a reference to the object as it moves around the display, similar to an address. Several indexes can be deployed simultaneously to allow for tracking of multiple targets. The purpose of the index is to assign priority to specific areas of the visual field for further processing. The indexes do not contain any feature information and are thought to update automatically as targets move. One way to modify the theory to account for my results would be to think of the indexes as visual vectors. The visual vector contains the current location of the target and the direction of the target. The visual vector is updated throughout the tracking period to reflect the location of the target and its direction. Visual indexes only attach to targets, so it is unclear how this theory can account for my finding that distractor motion is also used during tracking. Pylyshyn (2006) claimed distractors receive inhibitory tags instead of indexes. Unlike indexes, the inhibitory tags do not provide a way for attention to move to objects. Instead, they attach to objects to effectively block attention from these objects. It is possible that the inhibitory tags are similar to the proposed vectors, although it seems unlikely. To create the vector, an object would need to receive attention to process the motion of the object. Attention cannot move to objects with inhibitory tags. Thus, it is unclear how the visual index theory can account for my finding that distractor motion is processed during tracking.

The multifocal theory of attention proposes independent foci of attention are used to attend to multiple locations simultaneously (Cavanagh & Alvarez, 2005). Targets attract foci of attention and a control process keeps the foci of attention centered on targets throughout the tracking period. Everything about the targets is processed by the foci of attention (e.g. location, color, motion). The multifocal theory of attention could account for my findings if the control process uses motion information to guide the foci of attention. The control process may use the velocity signals from the foci of attention to predict the future locations of targets. The foci of attention move to the predicted locations. The control process may use a limited resource for this process, so only a few predictions can be made simultaneously (Alvarez & Franconeri, 2007; Bettencourt & Somers, 2009; Fencsik et al., 2007; Horowitz & Cohen, 2010; Vul et al., 2009). The multifocal theory of attention does not describe any mechanism that would allow for processing of distractors because distractors do not receive foci of attention. It may be argued that distractors are processed when they enter the region covered by attention. The control process may not be able to distinguish between a target and distractor when both are within a focus of attention. In this case, the control process may use the motion of the distractor to predict its next location, accounting for my finding that distractor motion is used during tracking.

The model of multiple identity tracking (MOMIT) is different from the theories discussed so far because it is a serial process (Oksama & Hyönä, 2008). A single focus of attention must move to each target to bind the location of the target to the identity of the target. An object needs attention to be identified as a target and to be bound to a spatial location. The identity-location binding is stored in memory when attention moves to another object. Attention moves to the location of the weakest target location-identity binding. If the object has moved, attention moves to the nearest object and uses identity information to determine if the object is the target. Motion may be part of the information bound to the locations of targets in memory, and may be used to help determine if the selected object is the target. The proximity of distractors to targets influences the strength of location-identity bindings. The location-identity binding is weaker for a target near a distractor, so attention will be directed to the crowded target. Motion information may be used to determine whether a target and distractor near one another will move closer together or move farther apart. In this way, the motion information of targets and distractors may be used to predict when a crowding event will occur, so that the strength of the location-identity bindings can be adjusted accordingly.

The probabilistic assignment model already describes how motion might be used in multiple object tracking (Vul et al., 2009). In the first stage of tracking, the locations and motion information of objects are extracted. This information is used to predict the next locations of targets and distractors. The model assumes people know how predictably the objects will move and uses this to determine the extent to which motion information is used during tracking.

Motion is weighted more heavily in these predictions when the object motion is assumed to be predictable. As the assumption about the predictability of the object motion decreases, the weighting of motion decreases. The second stage of tracking uses the predictions to assign identities of target or distractor to all objects in the display. A limited-capacity, flexible resource, such as attention or memory, determines the sampling rate of position and velocity information. Tracking errors arise because there is noise in the perceptual system that estimates the positions and motion information of targets and distractors. Texture motion may influence tracking because it biases the estimation of velocity in the first stage of tracking in the direction of the texture motion. This bias results in incorrect predictions about the future locations of targets and distractors that may lead to identity errors in the second stage of tracking.

Current theories of tracking can be elaborated to include the use of motion information during tracking. However, it is difficult to determine how the visual index theory can account for the finding that distractor motion is processed during tracking. Each theory allows for the possibility that motion information is used to predict the future locations of objects during tracking. MOMIT also allows for the possibility that motion is used as a distinguishing feature for objects. In the following section, I will examine evidence that the visual system uses motion information in these ways.

How is motion used?

One way the visual system may use motion information is to predict where things are going. Studies of apparent motion suggest predictions may be used to fill in the motion percept between the discrete locations of the target (Hogendoorn et al., 2008; Ramachandran & Anstis, 1983; Schwiedrzik et al., 2007). Ramachadran and Anstis (1983) showed that viewing apparent motion perceived in one direction biased the percept of ambiguous apparent motion in that direction, a phenomena they call visual momentum. The visual system may use previous motion information to resolve ambiguities in apparent motion displays. The visual system may also use motion information to predict where objects are going when guiding action. To catch a ball, for example, we need to know where it will be in the future, so that we can place our hand in the correct location. If we direct our hand to the current location of the moving ball, it will be in a new location by the time our hand completes its movement. Instead, motion information may be used to extrapolate the location of the ball (Land & McLeod, 2000; Nijhawan, 1994; Regan & Gray, 2001; Soechting & Flanders, 2008; Soechting, Juveli, & Rao, 2009). Similarly, predictions from motion may be used to prevent collisions with moving objects as we navigate through the environment (Gray & Regan, 2000; Regan & Gray, 2001). My results are consistent with previous research that shows motion is integrated over the whole object to form a percept of the object's motion that is used for prediction (Lorenceau, 1996; Qian et al., 1994; Weiss et al., 2002). When conflicting motions are integrated, the motion information does not match the physical motion of the object. Thus, predictions about where the object is going are incorrect.

The visual system may also treat motion information as a feature that can be used to discriminate one object from another. This would be akin to knowing that targets are blue and distractors are green. If a target is moving upward and a distractor is moving downward, motion information can be used to distinguish between the two objects. It is more difficult to distinguish the target from the distractor when they move in the same direction (Suganuma & Yokosawa, 2006). Sugnauma and Yokosawa (2006) found that tracking accuracy was lower when targets and distractors had the same motion trajectory than when they had different trajectories. They suggest that objects with matching trajectories are grouped together so that they were treated as a single object. The visual system groups common motion together to segregate the motion of one object from another (Burr & Thompson, 2011), giving rise to form from motion. The textured stimuli in my experiments are a good example of form from motion. When the targets are stationary on the textured background, they cannot be seen. However, when each point of the texture inside a small square region of space moves in one direction and the background texture remains stationary, a square is perceived. The motion inside the square is different from the motion of the background so the visual system parses the square and the background into different objects. Grouping common motions for segregation also gives rise to motion transparency, the percept of one moving surface sliding over another (Burr & Thompson, 2011; D. C. Burr et al., 2009; Qian et al., 1994). If motion is used as a feature in tracking, conflicting motion may impair the process of matching motion during tracking. When the motion of the texture is integrated with the motion of the object, this could result in two objects moving in different directions having the same motion information. For example, combining an upward object motion with a downward texture motion results in the same motion information as combining a downward object motion with an upward texture motion. If one of these objects is a target and one a distractor, motion information cannot be used to determine which object is the target.

Object correspondence

A crucial function of the visual system is to identify objects and maintain their identities as they move. The information entering the visual system changes as objects move, yet we do not perceive different objects every time this information changes. Instead, we perceive a single moving object. The ease with which we are able to do this belies the complexity of the task. In order to perform this task, the visual system must form a representation of the object that can be updated to reflect changes in the object caused by motion. This includes updating the location of the object over time. This process is called object correspondence and is of such importance as to warrant study by a number of fields. In fact, the MOT task was originally developed as a way to understand how we are able to maintain stable percepts of objects in our environment. The work in this dissertation shows that motion information may be important to object correspondence.

The task of object correspondence is binding the identity, location, and features of an object into one representation. Kahneman and colleagues (1992) proposed binding is achieved with object files. Object files are temporary representations of objects created by the visual system. The object file binds the location of an object to the features of the object. Similar to visual indexes, object files are accessed by locations, not by any feature of objects. The location, or address, of the object file is updated as objects move. Unlike a visual index, the object file may contain feature information, such as color and shape, as well as identity information. The number of object files that can be maintained are limited and the resolution of the information in the object file is limited by the complexity of the object. The object file is updated when the object changes. Stable representations of objects depend on these updates. If the object changes and the object file is not updated, a new object is perceived. If the object file is maintained when the features of the object change and when the object moves, how does the visual system know the difference between a changing object and a new object? Put another way, what determines whether a new object file is created or the current object file updated? One proposal is spatiotemporal continuity (Kahneman & Treisman, 1992; Scholl, 2007). If the path between two successive presentations of an object in different locations is spatiotemporally continuous, the object is perceived as changing. If the path is not spatiotemporally continuous, a new object is perceived.

Many lines of evidence have converged to suggest that spatiotemporal continuity is the key to object correspondence. Some researchers suggest that spatiotemporal continuity is prioritized over feature information (Burt & Sperling, 1981; Kahneman & Treisman, 1992; Navon, 1976; Yi et al., 2008 but see Hollingworth & Franconeri, 2009). The strongest evidence for prioritizing spatiotemporal information is the tunnel effect (Burke, 1952; Scholl, 2007). An object passes behind an occluder and reappears looking very different. If the second object reappears as if the object had moved continuously behind the occluder, a single object is perceived as passing behind the occluder. The effect is so strong that a kiwi can pass behind the occluder and emerge as a lemon and be perceived as a single moving object (Flombaum & Scholl, 2006). The addition of a temporal delay between the occlusion of the first object and the reemergence of the second object results in the percept of two separate objects (Burke, 1952). One object moves behind the occluder and another object emerges. Spatiotemporal properties also mediate apparent motion percepts (Bowne et al., 1989; Castet, 1995; Ramachandran & Anstis, 1983, 1986). An object flashed briefly in one location, removed, and then another object flashed briefly in a new location often results in the percept of a single object moving from the first location to the second location (Burr & Thompson, 2011; Nijhawan, 1994; Wertheimer, 1912). Objects in the apparent motion display are perceived as travelling the shortest distance (Ramachandran & Anstis, 1986; Ullman, 1979), even if that means swapping all other features (Burt & Sperling, 1981; Kolers & Pomerantz, 1971; Navon, 1976; Scholl, 2007). Investigations of MOT are consistent with these studies. We can track objects using spatiotemporal information, even when the features of the objects change (Makovski & Jiang, 2009). The prioritization of spatiotemporal continuity over feature information in object correspondence suggests that motion information is more likely to be used for prediction than as a distinguishing feature during tracking.

General Conclusions

The work in this dissertations shows motion is used to maintain the identities of moving objects. Motion may be used to predict the future locations of objects or it may be used as a feature to distinguish targets from distractors. Interferences with this process, such as conflicting motion or a poor motion signal, may result in correspondence errors. This finding can be used in a number of ways outside the laboratory to improve performance on tasks that involve tracking. For example, an air traffic controller needs to be able to track several moving planes represented on a control panel. Improving the display so that it gives a strong motion signal for each object may improve his ability to successfully guide air traffic. For those of us not in field of air traffic control, this finding could be used to reduce traffic accidents. We track other cars while we drive to avoid collisions. Objects that often change direction are harder to track than objects that follow linear trajectories. Cars weaving in and out of traffic are more difficult to track than cars that do not change lanes frequently. To make it easier for other drivers to track your car, you should limit unnecessary lane changes. I started this dissertation by describing the difficulty our visual systems face in creating stable percepts of our environment. Motion information aids the visual system in this complex task. Recent technological advances have provided a plethora of devices to present dynamic visual information. As this technology continues to develop, engineers should be conscious of how the visual system uses motion information to guide interactions with these devices.

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